

Volume 10

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Number 12

# BULLETIN

of the

## American Association of Petroleum Geologists

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### CONTENTS

|  |                              |
|--|------------------------------|
| Construction, Theory, and Application of Magnetic Field Balances             |                              |
|  | By C. A. Heiland 1189        |
| Schweydar-Bamberg Types of Eötvös Torsion Balance                            | By C. A. Heiland 1201        |
| Torsion Balance Principles as Applied by the Original Eötvös Torsion Balance | By George Steiner 1210       |
| Oil and Gas Prospects of New Zealand   | By Frederick G. Clapp 1227   |
| Mechanics of the Balcones and Mexia Faulting                                 | By Lyndon L. Foley 1261      |
| The Problem of the Natural Reduction of Sulphates                            | By Edson S. Bastin 1270      |
| Geological Notes   |                              |
| A Photograph Model   | By W. K. Cadman 1300         |
| Unconformities in the Pennsylvanian  | By Henry Hinds 1303          |
| Barometric Leveling  | By Henry A. Ley 1305         |
| Geophysics at Colorado School of Mines                                       | By Max W. Ball 1305          |
| Oklahoma Survey Seventh Field Conference. Ouachita Mountains of Oklahoma     | By Charles N. Gould 1306     |
| Reviews  |                              |
| Petroleum Development and Technology in 1925                                 | C. A. Fisher 1309            |
| Oil-Bearing Formations of Southwestern Arkansas                              | U. S. Geological Survey 1310 |
| New Publications, Oklahoma Geological Survey                                 | Charles N. Gould 1311        |
| The Association Round Table  | 1313                         |
| At Home and Abroad   | 1316                         |
| Memorial   |                              |
| Charles Stirling Huntley   | By Earle Brown 1322          |
| Index to Volume 10   | 1323                         |

# THE BULLETIN

of the

## AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

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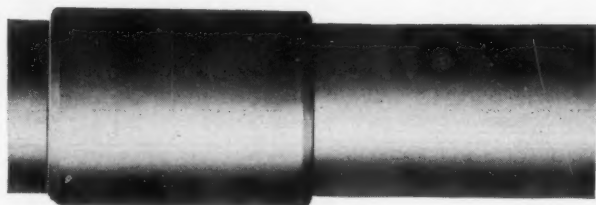
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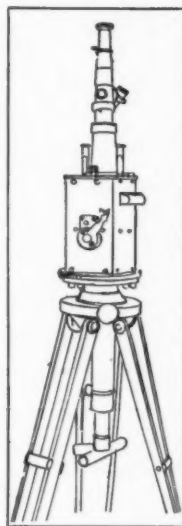
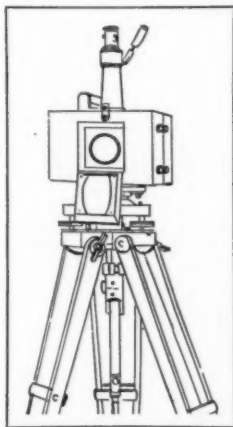
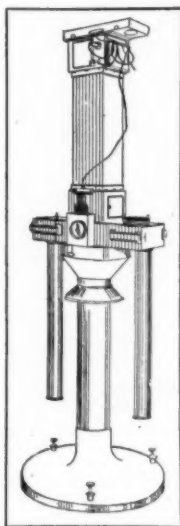


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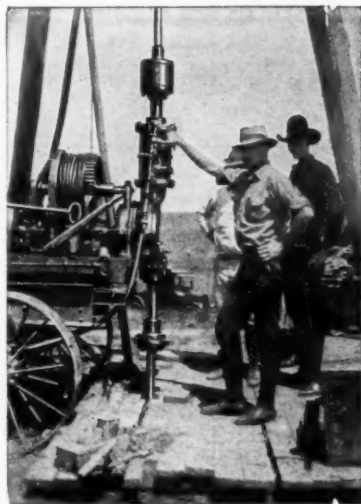
DECEMBER 1926

No. 12

### CONTENTS

|   |      |
|---|------|
| CONSTRUCTION, THEORY, AND APPLICATION OF MAGNETIC FIELD BALANCES . . . . .                                  | 1189 |
| By C. A. HEILAND . . . . .  |      |
| SCHWEYDAR-BAMBERG TYPES OF EÖTVÖS TORSION BALANCE. . . . .  | 1201 |
| By C. A. HEILAND . . . . .  |      |
| TORSION BALANCE PRINCIPLES AS APPLIED BY THE ORIGINAL EÖTVÖS TORSION BALANCE. . . . .                       | 1210 |
| By GEORGE STEINER . . . . .   |      |
| OIL AND GAS PROSPECTS OF NEW ZEALAND . . . . .  | 1227 |
| By FREDERICK G. CLAPP . . . . .   |      |
| MECHANICS OF THE BALCONES AND MEXIA FAULTING . . . . .  | 1261 |
| By LYNDON L. FOLEY . . . . .  |      |
| THE PROBLEM OF THE NATURAL REDUCTION OF SULPHATES . . . . .   | 1270 |
| By EDSON S. BASTIN . . . . .  |      |
| GEOLOGICAL NOTES  |      |
| A Photograph Model, <i>W. K. Cadman</i> . . . . .   | 1300 |
| Unconformities in the Pennsylvanian, <i>Henry Hinds</i> . . . . .   | 1303 |
| Barometric Leveling, <i>Henry A. Ley</i> . . . . .  | 1305 |
| Geophysics at Colorado School of Mines, <i>Max W. Ball</i> . . . . .  | 1305 |
| Oklahoma Survey Seventh Field Conference. Ouachita Mountains of Oklahoma, <i>Charles N. Gould</i> . . . . . | 1306 |
| REVIEWS   |      |
| Petroleum Development and Technology in 1925, <i>C. A. Fisher</i> . . . . .                                 | 1309 |
| Oil-Bearing Formations of Southwestern Arkansas, <i>U. S. Geological Survey</i> . . . . .                   | 1310 |
| New Publications, Oklahoma Geological Survey, <i>Charles N. Gould</i> . . . . .                             | 1311 |
| THE ASSOCIATION ROUND TABLE   |      |
| Membership Applications Approved for Publication, <i>J. P. D. Hull</i> . . . . .                            | 1313 |
| Volume I, <i>J. P. D. Hull</i> . . . . .  | 1314 |
| The Association Library . . . . .   | 1314 |
| Annual Membership Dues . . . . .  | 1314 |
| Geological Society of America . . . . .   | 1314 |
| AT HOME AND ABROAD  |      |
| Current News and Personal Items of the Profession . . . . .   | 1316 |
| MEMORIAL  |      |
| Charles Stirling Huntley, <i>J. Earle Brown</i> . . . . .   | 1322 |
| INDEX TO VOLUME 10 . . . . .  | 1323 |

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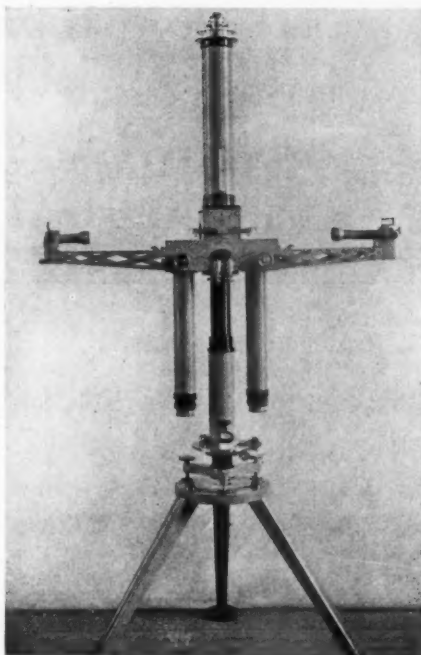
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DECEMBER 1926

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**CONSTRUCTION, THEORY, AND APPLICATION  
OF MAGNETIC FIELD BALANCES**

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C. A. HEILAND  
Colorado School of Mines, Golden, Colorado

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**ABSTRACT**

The paper describes the development and construction of magnetic field balances for measuring the vertical and horizontal intensity of earth magnetism. The main features of the theory are given and instructions to apply them. Success has been obtained with the instruments mainly over salt domes, iron-ore deposits, and igneous rocks such as granite ridges. Examples of such measurements are demonstrated. Literature.

---

**CONSTRUCTION OF MAGNETIC FIELD BALANCES**

Magnetic instruments were the first geophysical apparatus used for the exploration of mineral deposits. Especially in Sweden they were used for the discovery of iron ores. As not much accuracy was required for this purpose, the devices employed were rather crude surveying instruments. After the magnetic method had succeeded very well in iron-ore mining, it was desirable to find less magnetic deposits by improving the apparatus. Furthermore, it had been recognized that it is not necessary, for practical geological purposes, to measure the magnetic field entirely, but that the location of geologic disturbances is manifested sufficiently by one component of the magnetic field; however, if a determination of their extent and depth is desired, it is then necessary in most cases to observe two components. The component of the earth magnetic field which has the closest connection with disturbing causes is the vertical intensity;

it is at its maximum above the greatest accumulation of magnetic masses in the subsurface. An instrument, therefore, with which it is possible to measure the vertical intensity in the field in a simple

manner is the best for practical geological purposes. For further conclusions it is recommended to observe the horizontal intensity together with the vertical intensity.

Professor Adolf Schmidt, of the magnetic observatory in Potsdam, Germany, recently designed two such field instruments for the components mentioned, the so-called "field balance" (or local variometer) for the vertical and the horizontal intensity.

In the vertical field balance (Fig. 1) a double magnet is inclosed in an aluminum case; the magnet-system is balanced on a quartz knife edge resting on quartz bearings in the direction perpendicular to the magnetic meridian. If the center of gravity of this system were the same as the center of motion, the magnet would stand perpendicular, that is, it would show the direction of the magnetic vertical intensity; however, as the center of gravity is below the axis of rotation, the magnetic force is compensated at some point by the effect of gravity on the center of gravity. The angle of the inclination is a measure for the magnitude of the vertical component.

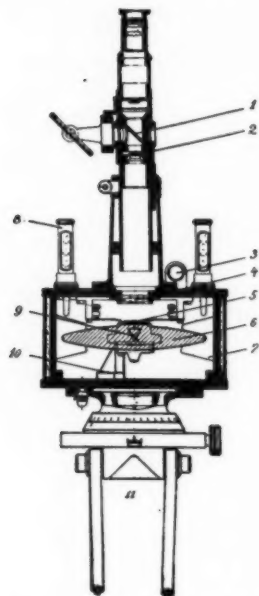


FIG. 1.—Cross-section of Adolf Schmidt's vertical field balance: (1) transparent glass plate; (2) glass plate with graduations; (3) level; (4), objective lens; (5) balance-system mirror; (6) magnet; (7) copper piece for damping; (8) thermometer; (9) quartz knife edge; (10) bearing; (11) tripod.

As the angle is very small, it is read by means of a telescope with autocollimational system. During transportation the system is lifted from its bearings and held fast by an arresting mechanism. The temperature of the inclosed mechanism is read from two thermometers. For taking the measurements the instru-

ment is put upon a tripod, the top of which may be turned and oriented in the direction perpendicular to the magnetic meridian.

The arrangement of the horizontal field balance (Fig. 2) is exactly the same in principle, except that the magnetic system stands vertical instead of horizontal and is tilted in the direction of the magnetic meridian by the horizontal intensity.

The advantages of these magnetic balances lie in the very simple constructional principle, in the speed of observations, and in the simplicity of the calculations, because a rising intensity corresponds simply to a rising scale-reading. Moreover, it is possible to carry but one tripod in the field for both the vertical and horizontal instruments, and the observer has no worries because the method of reading is the same for both.

It is now easy to transform the field balances into recording magnetometers by removing the telescopes and replacing them by a mirror attachment, using a suitable recording device (Fig. 3). The variation of the earth's field, which must be taken into consideration, then is recorded simultaneously with the field observations.

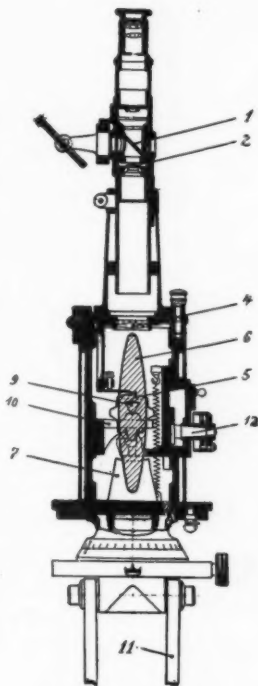


FIG. 2.—Cross-section of Adolf Schmidt's horizontal field balance. Legend same as in Figure 1; (12) arresting mechanism.

#### THEORY OF MAGNETIC FIELD BALANCES

A magnetic needle which is capable of rotation about an axis in any direction in space is influenced by a moment caused by the magnetic field of the earth. This moment can be computed theoretically and depends upon the magnetic strength of the system, the inclination, and the azimuth of its rotational plane and also the position of the north pole of the needle upon it. If the center of gravity does

not lie in the axis of rotation, a second moment is produced which depends upon the horizontal and vertical distance of the center of gravity below the axis of rotation, the weight of the system, and the inclination of the rotational plane. In the motionless state of the system both moments are counterbalanced. The formula representing this equilibrium has been stated in the author's paper, in *Zeitschrift für angewandte Geophysik* (1924), Heft 10 and 11, and looks a little

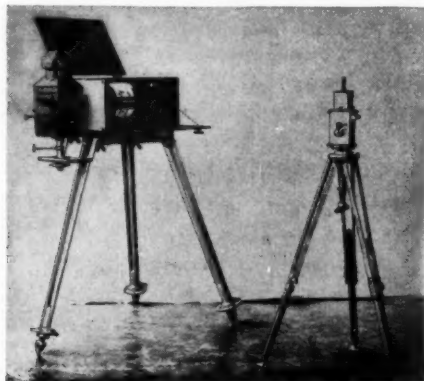


FIG. 3.—Horizontal field balance set up for recording variations, with mirror attachment and recording device.

complicated, but has the advantage that it is valid for all magnetic systems in any position the center of gravity of which does not lie in the axis of rotation. The formula becomes much simpler if the plane of rotation of the magnetic system is perpendicular to, or parallel to, the magnetic meridian, as in the position of use of the vertical and the horizontal balance.

*Theory of the field balance for vertical intensity.*—With the plane of rotation of the magnetic system oriented either at  $90^\circ$ <sup>1</sup> or  $270^\circ$ <sup>2</sup> to the magnetic meridian, then, from the previously mentioned formula the deflection,  $\phi$ , of the magnetic system:

$$\tan \phi = \frac{MZ + mga}{mgd}$$

<sup>1</sup> At  $90^\circ$  the "N" end of the magnets pointed to the east.

<sup>2</sup> At  $270^\circ$  the "N" end of the magnets pointed to the west.

wherein  $M$  signifies the magnetic moment of the system;  $Z$ , the vertical intensity of the terrestrial magnetism;  $m$ , the mass of the system;  $g$ , gravity;  $a$ , the horizontal, and  $d$ , the vertical, distance of the center of gravity from the axis of rotation.

Expressed in scale readings,  $S - S_0$ , wherein  $S_0$  is the scale reading for the position of equilibrium,  $MZ = mga$ , that is, for the horizontal position, and  $S$  is the observed scale reading, the deflection is

$$\tan \phi = \frac{S - S_0}{2f}, \text{ or } S - S_0 = 2f \left( \frac{MZ + mga}{mgd} \right)$$

wherein  $f$  is the focal distance of the lens above the balance-mirror. From this formula comes the formula for the use and application of the instrument. Putting  $S_0 = 0$  and supposing that the reading,  $S$ , corresponds to a known or supposed intensity,  $Z$ , and a new reading,  $S'$ , to the intensity,  $Z'$ , to be determined, it is:

$$S' - S = \frac{2fM(Z' - Z)}{mgd}, \text{ or } Z' = (S' - S) \frac{mgd}{2fM} + Z$$

$\frac{mgd}{2fM}$  is a constant for each instrument and gives the scale value of the instrument (the force in absolute measure causing a deflection of one scale division). If it is designated by  $\epsilon$ , the formula for use becomes

$$Z' = \epsilon(S' - S) + Z$$

The reading,  $S'$ , or the result, must be corrected for temperature changes, variation of the magnetic field of the earth, and change of the so-called "base position" of the instrument (hard knocks during operation of the instrument might cause the center of gravity of the magnetic system to be displaced slightly; therefore, on returning to the first, or base station, the reading,  $S$ , might not check with the initial reading taken there).

*Theory of the field balance for horizontal intensity.*—If  $\phi'$  is the deflection of the magnetic system of the horizontal field balance from the vertical zero position due to the horizontal component of the earth's magnetic field, then

$$\tan \phi' = \frac{MH - mga}{MZ + mgd}$$

wherein  $H$  = magnetic horizontal intensity, and

$$S - S_0 = 2f \left( \frac{MH - mga}{MZ + mgd} \right)$$

and similarly as for the vertical variometer,

$$S' - S = 2fM \left( \frac{H' - H}{MZ + mgd} \right) \text{ or } H' = (S' - S) \left( \frac{MZ + mgd}{2fM} \right) + H$$

and where

$$\frac{MZ + mgd}{2fM} = \epsilon$$

the formula for use is:

$$H' = \epsilon(S' - S) + H$$

The result is to be supplied with the same corrections as used with the vertical balance; moreover, it is necessary to add a correction because of the change of the vertical intensity.

#### APPLICATION OF THE FIELD BALANCES

At each station the tripod is set up and oriented to the magnetic north, the horizontal field balance is set upon the tripod, and about three readings taken. The balance is locked and released for each reading. Then the magnetic vertical field balance is set up and read in the same way, except that the balance is oriented first to magnetic east and then to magnetic west, or vice versa. Temperature and time of day are recorded in order to make the variation correction. From ten to twenty stations can be finished in one day. It is recommended to measure along loop lines and to repeat a base station twice a day in order to get informations concerning any displacement of the center of gravity in the magnetic system. Twice a month the scale value and temperature coefficient should be examined. Every instrument is supplied with auxiliary magnets for bringing back the reflected scale if it is out of vision, that is, for increasing the range of the instrument. In this case a correction is to be made accordingly. The daily variation of the earth field must be eliminated. For this purpose an instrument is placed approximately in the center

of the area to be surveyed, and either read visually every 5 or 10 minutes, or connected with a photographic recording device after the telescope has been replaced by a mirror attachment. Another possibility is the application of the so-called "chain method," by which the observations are made with two visual instruments by two observers at Stations A and B, then B and C, C and D, and so on, that is, on two consecutive stations simultaneously. Although the whole method of observation with the field balances is a relative one, it is possible to obtain results expressed in absolute measure if the value of  $Z$  or  $H$  for the base (or beginning) station is known. In this case the value of  $S$  corresponding to this  $Z$  or  $H$  is to be subtracted from the readings on all other stations, the difference multiplied by  $\epsilon$ , and the result added to  $Z$  or  $H$ ; thus  $Z'$  or  $H'$  is obtained. In order to get only the disturbances,  $\Delta Z$  and  $\Delta H$ , really caused by geological influences, one has to subtract from  $Z'$  or  $H'$  the normal value  $Z_0$  or  $H_0$  of the earth magnetism for each station. If neither  $Z$  and  $H$  nor  $Z_0$  and  $H_0$  are known, one makes the first or base reading,  $S$ , on a place supposed to be undisturbed, in this way getting directly  $\Delta Z$  or  $\Delta H$ .

The applicability of the magnetic method extends chiefly to the discovery of iron ores, as magnetite and hematite; magmatic intrusions, as granite, basalt, and porphyry ridges; and salt domes.

The accompanying figures show some examples of measurements above deposits of such a kind.



FIG. 4.—Measurements of magnetic vertical intensity made by the author above the salt dome near Segeberg, in northern Germany.

- Drill hole with gypsum and salt,
- hole without it.

..... Lines of equal anomaly of the magnetic vertical intensity; the -75 Curve embraces the areas with the shallowest location of the cap rock.

The first observations of  $\Delta Z$  above salt deposits were carried out by F. Schuh. They showed that the vertical intensity decreases above salt domes, probably because they have less magnetic material than the adjacent Pleistocene and Tertiary beds, especially above

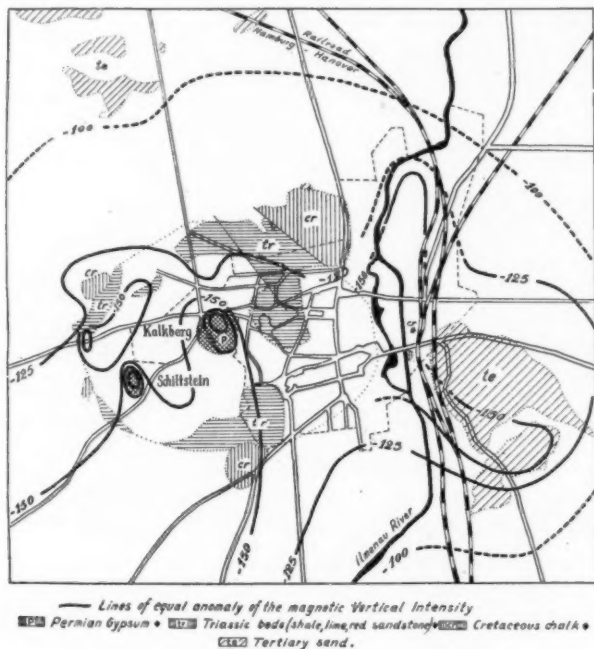


FIG. 5.—Measurements of the magnetic vertical intensity taken by the author above the salt dome at Lüneburg, northern Germany.

the cap rock. The author made similar measurements in Segeberg, Germany, where the surveyed area was well known by borings (Fig. 4). The observations give a very close connection between the geological situation and the maximum disturbance of the vertical intensity, showing a minimum at the Kalkberg, which is the outcrop of the top of the cap rock. A similar result was obtained above the salt dome at Lüneburg, Germany (Fig. 5), where the measurements

showed two minima corresponding to two outcrops of the gypsum, the Schiltstein, and the Kalkberg.

Measurements were made by the author also above the magnetic deposits at Berggiesshuebel, in Saxony (Fig. 6), with both the vertical and the horizontal field balances. In the part surveyed the

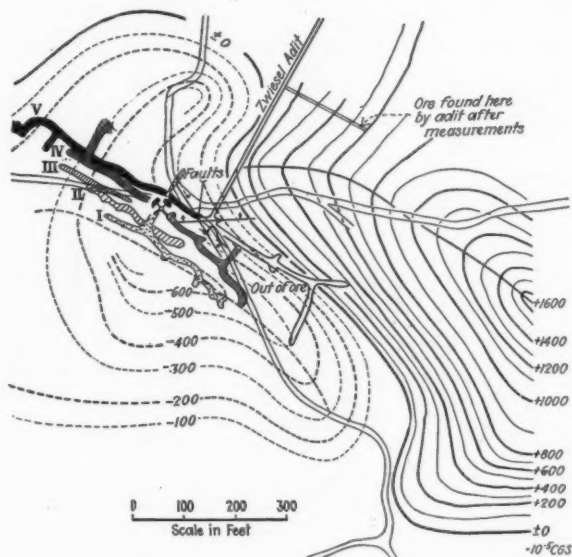


FIG. 6.—Results of magnetic measurements obtained by the author above the Berggiesshuebel magnetite deposits in Saxony.

deposit dipped about  $60^{\circ}$  N. Therefore the vertical intensity increases rapidly from the south up to the maximum near the outcrop; then decreases slowly northward. The horizontal intensity is zero near the outcrop and shows a maximum south of the deposit and a minimum less than the maximum in the north. This is the normal effect caused generally by magnetite deposits, which, however, is only the case in the eastern part of the area; in the western part, separated from the former by a fault and displaced to the south, the polarity of the magnetism is reversed (north-magnetism); there-

fore the vertical intensity is at a minimum above the outcrop. The location of the part having normal magnetism east of the fault was not known when the measurements were made, and attempt was made to find it by a tunnel lengthening the Martin mine and a cross-adit going to the south, in the supposition that the deposit was displaced in this direction, but in vain. After these unsuccessful experiments the magnetic measurements showed without doubt a comb-line of the vertical intensity (a line connecting the points with the

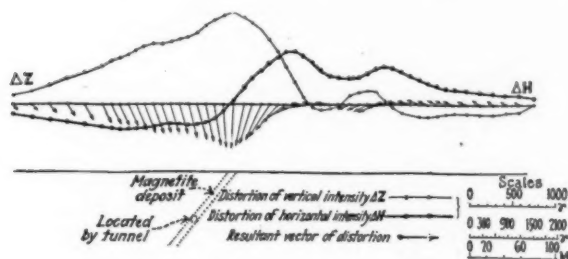


FIG. 7.—Profile across the magnetite deposits, showing the magnetic vertical and horizontal intensity and the disturbance vectors (representing the magnitude and inclination of the disturbance of total intensity equal to the vectorial sum of the vertical and the horizontal intensity of each station).

greatest disturbance and corresponding to the outcrop) north of the left part of the mine, and indicated the displacement of the eastern part along a fault striking from SE. to NW. This interpretation from the magnetic survey was confirmed half a year later by a tunnel driven eastward from the Zwiesel adit.

Those relations between the earth's magnetism and geological conditions are made much clearer by representing the results with vectors of disturbance, as shown in the sketch (Fig. 7).

#### DISCUSSION

H. R. THORNBURGH: I should like to ask the amount of time necessary to occupy a station.

C. A. HEILAND: The time required for one observation with the vertical or horizontal variometer is about five minutes.

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## SCHWEYDAR-BAMBERG TYPES OF EÖTVÖS TORSION BALANCE<sup>1</sup>

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### ABSTRACT

The general principle of the torsion balance is explained and the development of the automatic recording type is briefly described. Details on the large model Schweydar-Bamberg are given. Also a small model of this type has been developed by adopting a new shape of the balance beam. Future possibilities in the construction of small torsion balances are discussed. A list of references is appended.

*Principle of torsion balance.*—For his gravitational researches Baron Roland von Eötvös designed an instrument which made it possible to observe gravitational data with an accuracy previously unobtainable, namely, the torsion balance. The principle of this instrument, that is, a horizontal bar loaded at its ends by two weights and suspended from a thin wire, thus reflecting very small horizontal attractions, was already known at that time, since Cavendish had used it for the determination of the gravitational constant, and Coulomb for electric and magnetic investigations.

Eötvös was the first who made the torsion balance suitable especially for the solution of practical geological problems by changing the design of the torsion balance already known. He suspended one of the loading masses below the horizontal part of the beam. This improvement enabled him not only to measure horizontal directing forces, as was possible with the first type, but also the alteration of gravity in horizontal direction, the so-called "gradient of gravity." A deflection of such a balance with two weights in different levels is produced by irregularities in the subsoil, since the directions of attractions of such masses are different at the two weights, thus causing a small horizontal component. Naturally there occur no differences in those directions of attractions over the center of heavy masses in the subsoil, but they reach their highest amount over the edges, meaning that the greatest deflection is produced where the gradient of gravity is the largest.

The described balance system is inclosed in a triple casing in order to protect it against air currents and temperature changes. Generally two balances by the side of each other are used in the same instrument. The deflections of the two beams are observed either visually in three azimuths, or the instrument is moved automatically in these three positions, taking records photographically after the balances have come to rest.

### DEVELOPMENT OF BAMBERG BALANCES

Baron Roland von Eötvös did not supply his field instruments with automatic and photographic recording arrangements because he was afraid they might have a disadvantageous influence upon the measurements and fail to work in the field. The experiments with photographic recording device which were carried out by O. Hecker

<sup>1</sup> Read by Donald C. Barton before the Association, Dallas meeting, March, 1926

and continued by W. Schweydar showed, however, that the results were not influenced disadvantageously by the recording device,

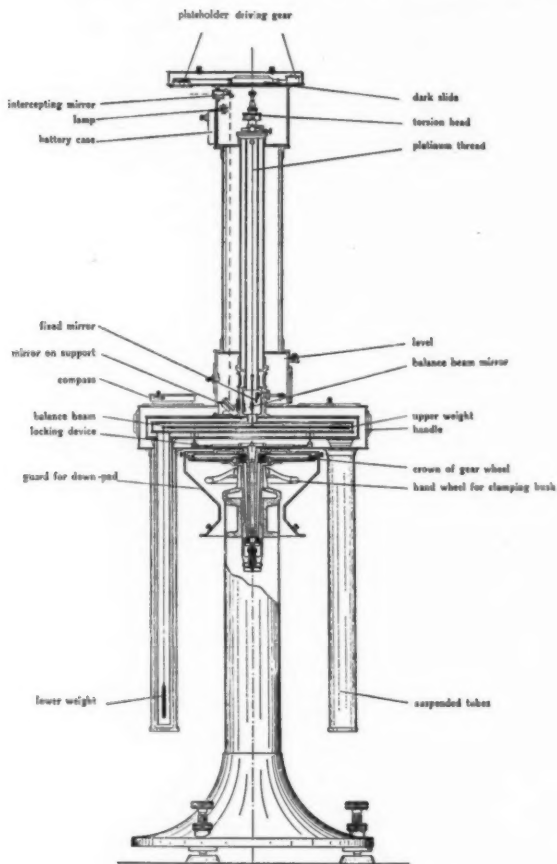


FIG. 1.—Large torsion balance, system Schweydar-Bamberg

and that on the other hand the observer saved labor and time because the measurements were taken quicker than with a visual instrument, even though by any accident the recording device

should fail to work at any time. In the beginning the instruments used by Hecker and Schweydar were made by the mechanician Fechner, of Potsdam, and carried the recording device on the end of the balance box.

#### CONSTRUCTION OF BAMBERG BALANCES

W. Schweydar improved the recording arrangement by placing the photographic device over the torsion heads, thus simplifying the shape of the instruments and increasing the magnification. Torsion balances of this kind are now manufactured by the firm Bamberg (Askania Werke) in Berlin. In its main features the Bamberg instrument (Fig. 1) has the same construction and nearly the same measurements as the Eötvös balance, that is, the same in the length and thickness of the torsion wire, in the length of the balance beam, and in the weight and the depth of the suspended cylinder below the balance beam. The sensitiveness, therefore, is also nearly the same. The photographic plates are read by means of glass scales with 0.5 mm. divisions; the gradient corresponding to a deflection of one-tenth of such a scale division which must be estimated amounts to  $0.5 \times 10^{-9}$  dynes, or 0.5 E (0.5 Eötvös units corresponding to about 0.000,000,000,001 of the normal gravity). Furthermore, the Bamberg instrument has arresting devices for the beam and for the suspended weights. The hanging tubes can be unscrewed for transportation. Visual readings of the balance deflections are also possible. A special damping arrangement is provided which shortens the time required in each azimuth for the reading from 60 to 40 minutes as desired. For very rapid temperature changes an eiderdown pad may be wrapped around the instrument without hindering the rotation.

#### MANUFACTURE OF THE INSTRUMENTS

The material for the two outer cases is aluminium; for the inner one, copper. The upper weight is made of gold, the lower one of brass filled with lead; in the smaller type of instrument, to be dealt with a little later, both cylinders are of gold. The casings are isolated from each other so that there is by no means a transmission of heat. The torsion wires are treated very carefully. A roll of platinum-

iridium thread is cut in proper length and the ends clamped very firmly on two clamps suitable for the torsion head and the balance beam. The wire is given again and again mechanical and heat treatments in order to make its elastic hysteresis as small as possible. The elastic properties and the temperature coefficients of the wires are carefully examined and the best selected. In the summer of 1924 the production of Bamberg balances was about one a month; in 1925 it increased to four or five, and reached its highest output in December, 1925, with twelve.

#### TERRAIN-CORRECTION

The influence of the terrain on torsion balances must always be taken into consideration. The shape of the terrain is determined usually by leveling around each station along concentric circles in different azimuths.

The Bamberg instrument has a smaller tripod than the Eötvös torsion balances in order to make it more convenient to transport; therefore the effect of an irregular terrain upon the Bamberg is somewhat greater. Not only for this reason, but also because it is impossible to use the terrain formulae given by Eötvös in cases where the ground within a distance of three meters of the instrument is not in the shape of a simple plane and conditions do not permit it to be made a flat or plane surface by artificial means, W. Schweydar has computed formulae<sup>1</sup> which represent the influence of the terrain more exactly than the Eötvös formulas.<sup>2</sup> His method is based upon the representation of differences in height around the station, upon the different circles by Fourier series. By use of this principle the influence of the nearest surroundings may be determined in the same manner as the farthest, that is, by measurements of differences in height along concentric circles. Furthermore, Schweydar's method is more accurate because there are more circles provided (1.5, 3, 5, 10, 20, 30, 40, 50, 70, and 100 meters). Without changing the final formula, even very irregular terrain may be determined by leveling in sixteen, instead of eight, azimuths.

<sup>1</sup> *Zeitschr. f. Geophysik*, Vol. 1 (1924-25), Heft 3, pp. 81-89.

<sup>2</sup> Of course the application of the formulas is also possible to an Eötvös instrument.

## SMALL TYPE SCHWEYDAR-BAMBERG (Z-SHAPED BEAM)

Several attempts have been made to reduce the size of the torsion balance. The consequence of a reduction of the important dimensions, however, is a considerable diminution of the sensitivity of the instrument. If one diminished all lengths ( $l$ , half the length of the beam;  $h$ , distance of lower weight from beam, length of the torsion wire;  $D$ , distance mirror-scale) by one-half, such an instrument would have a sensitivity for gradients and curvature values of only one-sixteenth of the large balance. It would be possible to compensate this loss of sensitivity by reducing the diameter of the torsion wire by one-half (because the torsional coefficient is proportional to the fourth power of the radius), but then the wire would have to be made of another material, because one wire half as thick as another has only a quarter of its tensile strength. This method, however, is not to be recommended because of the following reasoning:

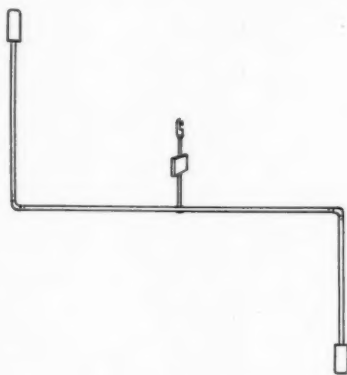


FIG. 2.—Z-shaped beam

Suppose that in the large torsion balance the balance beam is deflected by a gravitational moment and by another moment, amounting to 10 per cent of the former, produced by disturbing influences such as air currents or something similar. Now suppose that by halving all lengths the gravitational moment is diminished by a quarter of its previous amount, and suppose this diminution has been compensated only by decreasing the diameter of the wire; it follows that in this case the *disturbing effect due to non-gravitational causes increases to 40 per cent of the gravitational influence*.

In order to avoid this disadvantage connected with a compensation of the reduction of size merely by diminishing the diameter of the wire, W. Schweydar retained the length of the beam and also approximately the distance of the upper and the lower weight, but

placed the upper one on a vertical rod, about the same distance above the horizontal part of the beam as the lower one is below.

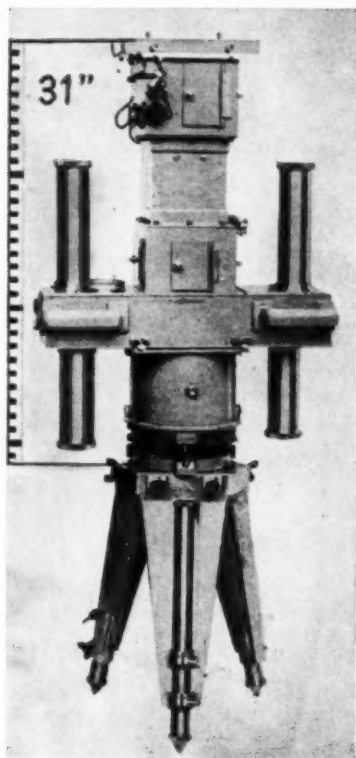


FIG. 3.—Small torsion-balance, system Schweydar.

Thus the beam was made in the shape of a Z (Fig. 3). Although with this arrangement the path of light from the balance mirror to the photographic recorder is shortened, the shortening is compensated by double reflections. The length of the torsion wire is halved, but the consequent loss of sensitivity is overcome by a small reduction of its diameter.<sup>1</sup> The sensitivity of this new small Z-type balance is about  $0.7 \times 10^{-9}$  C.G.S. (for one-tenth scale division of the glass plate with 0.5 mm. units) and about  $0.6 \times 10^{-9}$  C.G.S. for curvature values (1.4 and 1.2 for 0.1 mm.).

This small torsion balance with the Z-shaped beam has, furthermore, a great advantage over *all* other small types. In spite of the reduced size, the center of gravity has the same distance from the ground as in the large instrument;

therefore an extraordinarily high tripod can be eliminated, such as is required with all other small types in order to avoid too large an influence of the terrain. Also smaller and lighter observation houses

<sup>1</sup> The constants of the instrument are: length of balance beam, 40 cm.; vertical distance between weights, 40 cm.; size of each weight, 21 gm.; torsion constant of torsion wire, 0.44; four times focal distance, 3,680 scale units; constant,  $K$ , 15,600 C.G.S. units.

may be used. On the other hand, by using tripods as high as required for other small types of balances it is possible to diminish the terrain correction and therefore dispense with part of the labor connected with the leveling in the field.

#### FURTHER REDUCTION OF TORSION-BALANCE DIMENSIONS

The consideration previously made, that by compensating a diminution of the size of the balance merely by a reduction of the diameter of the torsion wire, one increases the disturbing influences, is valid only if the balance casings of smaller types are not an improvement over those of the larger ones. In the Z-shaped torsion balance, as compared with the larger instrument, a small reduction was made in the wire and a much tighter casing was introduced. The new shape of the beam also favors observation of these principles, because it is not necessary or possible to unscrew the vertical tubes. The best way to avoid all disturbing influences certainly would be to inclose the instrument entirely in a vacuum, a possibility very near, it is true, but not as yet realized. In the future the problem of the construction of the small torsion balance probably will be solved by a combination of all three factors mentioned, namely, Z-beam system, reduction of the diameter of the torsion wire (also selection of the material with the best elastic properties and greatest tensile strength), and inclosing of the entire instrument in a vacuum.

#### DISCUSSION

P. S. SCHOENECK: How many men are necessary to transport the Bamberg instrument? What is the advantage in having an automatic photographic recording and rotating device, inasmuch as one member of the crew can easily arrange to be present to make observations?

C. A. HEILAND: Two men are necessary for transporting. The main advantage of the automatic arrangement is that the temperature conditions around the instrument are not changed at all during the observation, since the door of the house is not opened. Every observer of visual instruments knows that the balances start moving as soon as he stays too long with the instrument, therefore making exact readings difficult. If, furthermore, the observer is not reliable, it can happen that he writes down results without having been with the instrument. Cases like that have actually occurred. For unfavorable climatic or soil conditions it is not only more agreeable for the observer to stay in the

camp or in town, but he can make calculations and plotting while the instrument is working. During inundations it may be possible to set up a recording instrument, but not a visual one, since it is very difficult and disagreeable for a man to walk to the instrument every hour. Working with a recording instrument the observer can do surveying work far away from it without being bound to return every hour.

DONALD C. BARTON: It is interesting to notice that although Eötvös designed his torsion balance thirty-five to forty years ago, the new z-shaped balance is the first practical alteration or improvement of the fundamental design of the balance that Eötvös invented. The balance system is the same in the Süss types, the Hecker types, the older Schweydar-Bamberg types, and the Shaw-Oertling types. The difference between those types is essentially that of details of the housing, of the manner of observation, and, in the automatic instruments, in the presence of some type of automatic registration. Rybar, of Budapest, is reported to have perfected a diminutive instrument somewhat along the Eötvös original design. Kilchling, of Freiburg, has designed a new type, and a Russian physicist also has designed a new type. Several other physicists are working on radically new designs of balance. The z-shaped balance is the only one of these new designs of the Eötvös torsion balance that is in practical use at present.

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## TORSION-BALANCE PRINCIPLES AS APPLIED BY THE ORIGINAL EÖTVÖS TORSION BALANCE<sup>1</sup>

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### ABSTRACT

With the original type of torsion balance three to four stations a day can be taken with a crew of three men and two light trucks with a large instrument, or two men and one truck with the new smaller instrument. The distance between stations depends upon the type of the survey and the conditions of terrain and structure. The observed gradient must be corrected for terrain effects. The principle of interpretation of torsion-balance results is that the gravity gradient is toward the heavier mass and is the greater the heavier the mass, the nearer the heavy mass is to the surface, and the steeper its flank. In the case of a dome such as a salt dome, heavier than the country rock, the gradient is toward the center of the dome, is zero on top of the dome, and is opposite in direction on opposite sides of the dome. If the dome is lighter than the country rock, the gradient is away from the dome. The gradient existing above such a dome is illustrated by the results of the surveys of two salt domes in the Gulf Coast. In the case of an anticline the gradient is toward the axis. In the case of a fault, the gradient reverses across the fault, but differs in intensity on the up- and down-throw sides of the fault. The gradient relations above a series of hypothetical faults and folds are illustrated by the results of a torsion-balance survey in Texas. The irregular gradient conditions caused by irregular subsurface structure are illustrated by a torsion-balance survey in the vicinity of the Kellum lease in the Powell field, Texas.

### INTRODUCTION

The torsion balance designed and used by Eötvös was made in the establishment of Süss, in Budapest, Hungary.

After the death of Eötvös in 1919 the Hungarian government founded the Eötvös Geophysical Institute for the purpose of carrying on the researches begun by Eötvös. The establishment of F. Süss continued to manufacture the torsion balances, while the Eötvös Geophysical Institute attended to all scientific matters, preparing the torsion wires and determining the constants of the instruments. The application of the instrument made by these establishments is described in this paper.

### EXECUTION OF SURVEYS

The distance between gravity-observation stations depends mostly upon the type of survey. For a preliminary survey the sta-

<sup>1</sup> Presented before the Association at the Dallas meeting, March, 1926.

tions may be half or even three-fourths of a mile apart. For the outlining of a discovered structure or determining locations for drilling, the stations may be as near as 200 feet to each other. The structure of the land and also the terrain conditions influence the distance between stations.

The gravity observations may be made either in day- or nighttime, or in both, depending upon the number of stations to be made in 24 hours. The torsion balance must be observed in three azimuths. The beam must come to rest in each azimuth, which takes, with a margin of safety, 45 to 50 minutes each. The readings are repeated in one, two, or in all three azimuths. The writer's practice is to allow 60 minutes for the beam to come to rest in its first position, then 50 minutes for each of the remaining positions. He usually repeats the readings in the first and second azimuths, which give a double check for all four differential quotients. The time needed for one station is, altogether, 260 minutes.

Under normal conditions only two stations can be made in the daytime; three or four stations can be made in 24 hours.

At each station two different quantities must be determined. First, the intensity of the gravity gradient<sup>1</sup> itself, which is determined by the torsion balance, and second, the influences of the surroundings, which are determined by the plane-table method. The terrain effects must be deducted from the observed full values.

To determine the terrain effects, the irregularities of the terrain must be known, for which purpose the elevation of the ground is read in eight azimuths, 45° apart, around the point of observation. Depending upon the character of the surroundings, these readings are carried out to a distance of 5, 20, 50, or 100 meters. The inclination of the ground immediately at the station has a great influence on the observed gradient and is measured with a clinometer made for the purpose. As the terrain effects depend also on the specific gravity of the irregular masses, this is likewise measured with a convenient and suitable apparatus. The form illustrated in Figure 1 is used to calculate all the terrain effects. As the torsion balance is influenced by the changes in temperature the instrument must be pro-

<sup>1</sup> The gravity gradient is the variation of the value of gravity per horizontal centimeter. The unit of measurement used by Baron Eötvös is  $1 \cdot 10^{-9}$  dynes (per gram), and is, very closely, 0.000,000,000,001 the normal value of gravity.—EDRROR.

| Azim.                                  | 5m                            | 20m          | 50m             | 100m            | Station No. <u>128</u>              |                |              |
|--|-------------------------------|--------------|-----------------|-----------------|-------------------------------------|----------------|--------------|
| 1 N                                    | <u>+3</u>                     | <u>+3</u>    |                 |                 | Location <u>Donovan</u>             |                |              |
| 2 NE                                   | <u>+2</u>                     | <u>0</u>     |                 |                 | <u>Survey</u>                       |                |              |
| 3 E                                    | <u>+3</u>                     | <u>-2</u>    |                 |                 | <u>1/4 m N</u> } SE Corn            |                |              |
| 4 SE                                   | <u>+2</u>                     | <u>-1</u>    |                 |                 | <u>3/8 m W</u> }                    |                |              |
| 5 S                                    | <u>+3</u>                     | <u>+9</u>    |                 |                 | Survey by <u>R.J.G.</u>             |                |              |
| 6 SW                                   | <u>+1</u>                     | <u>-2</u>    |                 |                 | Check by <u>C.B.H.</u>              |                |              |
| 7 W                                    | <u>+3</u>                     | <u>+2</u>    |                 |                 | Remarks                             |                |              |
| 8 NW                                   | <u>-1</u>                     | <u>-6</u>    |                 |                 |                                     | 5m             | 20m          |
| 1-5                                    | <u>0</u>                      | <u>-6</u>    | EAST<br>SIDE    | NORTH<br>SIDE   | 1+5                                 | <u>+6</u>      | <u>+12</u>   |
| 3-7                                    | <u>0</u>                      | <u>-4</u>    | -               | -               | 3+7                                 | <u>+6</u>      | <u>0</u>     |
| 2-6                                    | <u>+1</u>                     | <u>+2</u>    | WEST<br>SIDE    | SOUTH<br>SIDE   | 2+6                                 | <u>+3</u>      | <u>-2</u>    |
| 8-4                                    | <u>-3</u>                     | <u>-5</u>    | -               | -               | 8+4                                 | <u>+1</u>      | <u>-7</u>    |
| (2-6)<br>+(8-4)                        | <u>-2</u>                     | <u>-3</u>    | $\frac{E+W}{2}$ | $\frac{N+S}{2}$ | (2+6)<br>-(8+4)                     | <u>+2</u>      | <u>+5</u>    |
| (2-6)<br>-(8-4)                        | <u>+4</u>                     | <u>+7</u>    | -               | -               | (5+7)<br>-(1+5)                     | <u>0</u>       | <u>-12</u>   |
|  | 0.130                         | 0.0117       | -               | -               |                                     | 0.207          | 0.084        |
| 1-5                                    | <u>0</u>                      | <u>-0.07</u> | <u>-0.07</u>    | —               | (2+6)<br>-(8+4)                     | <u>+0.59</u>   | <u>+0.44</u> |
| 3-7                                    | <u>0</u>                      | <u>-0.04</u> | —               | <u>-0.04</u>    | XY = $\frac{\text{Mean}}{1.8}$ Sum  |                | <u>+1.13</u> |
|  | 0.002                         | 0.008        |                 |                 |                                     | 0.504          | 0.160        |
| (2-6)<br>+(8-4)                        | <u>-0.18</u>                  | <u>-0.02</u> | <u>-0.20</u>    | —               | (3+7)<br>-(1+5)                     | <u>0</u>       | <u>-2.03</u> |
| (2-6)<br>-(8-4)                        | <u>+0.37</u>                  | <u>+0.06</u> | —               | <u>+0.43</u>    | (—) = $\frac{\text{Mean}}{1.8}$ Sum |                | <u>-2.23</u> |
|  | Sum                           |              | <u>-0.27</u>    | <u>+0.39</u>    | Mean                                | Spec.<br>Grav. | Volume       |
|  | $\frac{\text{Mean}}{1.8}$ Sum |              | <u>-0.30</u>    | <u>+0.43</u>    | 1.98                                | 2.02           | 2.38         |
| Slope { N&E; S&W +<br>Const. 1° = 7.60 |                               |              | XZ              | YZ              |                                     | 1.94           | 2.68         |
|  |                               |              |                 |                 |                                     |                | 520          |

Dr. GEORGE STEINER, HOUSTON, TEXAS

FIG. 1

tected as much as possible. In general, one uses for this purpose a double-walled and insulated portable house which is shown in Figure 5. This house is always set in the same azimuth, that is, with its door due north, to make its effect on the instrument, if any, constant. The triangular base of the instrument also has its definite position. The upper part of the torsion balance is turned due magnetic north, and azimuth No. 1 is read on a divided circle on the instrument. Azimuth No. 2 is  $+120^\circ$ , and azimuth No. 3 is  $+240^\circ$ . When the instrument is set in azimuth No. 1 all wires are released and the instrument is let alone. After 50 or 60 minutes the observer reads the position of both beams and the temperatures inside of the instrument. He then turns the instrument to azimuth No. 2 and allows it to come to rest, and then turns it to No. 3. For the sake of accuracy, two or three azimuths are read repeatedly.

On the reverse side of the forms, illustrated in Figure 2, the observer records his readings and corrects them according to the changes of temperature and his temperature constants. By adding any three consecutive  $120^\circ$  readings and dividing by three, he obtains the zero point of the wire, that is, the position of rest which the balance would take if there were no gravity effects acting on it.

The subsequent calculations are nothing other than the simple execution of formulas. For the sake of compactness in the forms, all mathematical signs are left out; the terms such as  $\frac{d^2U^1}{dxdz}$  are designated as follows:

$$\begin{aligned}\frac{d^2U}{dxdz} &\times XZ \\ \frac{d^2U}{dydz} &\times YZ \\ \left(\frac{d^2U}{dy^2} - \frac{d^2U}{dx^2}\right) &\times (---) \\ \frac{d^2U}{dxdy} &\times XY\end{aligned}$$

$\frac{d^2U}{dxdz}$  = the north-south component of the gradient.

$\frac{d^2U}{dydz}$  = the east-west component of the gradient.

$\left(\frac{d^2U}{dy^2} - \frac{d^2U}{dx^2}\right)$  and  $\frac{d^2U}{dxdy}$  = two magnitudes giving the curvature of the warping of the level surface, that is, of the surface perpendicular to the vertical.—EDITOR.

| Posit.       | Time         | Bal. # 1     | Temp.         | Correct | Mean  | Value   | Bal. #2 | Temp. | Correct | Mean    | Value |
|--------------|--------------|--------------|---------------|---------|-------|---------|---------|-------|---------|---------|-------|
| 1. 57°       | 8:30         | 148.4        | 11.8          | 148.4   |       |         | 433.4   | 12.0  | 433.4   |         |       |
| 2. 177°      | 9:30         | 150.2        | 10.1          | 150.1   | 148.7 | +1.4    | 431.6   | 10.3  | 431.3   | 432.7   | -1.4  |
| 3. 297°      | 10:30        | 147.9        | 9.1           | 147.7   | 149.1 | -1.4    | 433.9   | 9.3   | 433.4   | 432.5   | +0.9  |
| 4. ....      | 11:30        | 149.6        | 8.5           | 149.4   | 149.4 | 0.0     | 433.6   | 8.7   | 432.9   | 432.4   | +0.5  |
| 5. ....      | 12:30        | 151.7        | 5.8           | 151.2   |       |         | 432.2   | 6.0   | 431.0   |         |       |
| A<br>2' + 3' | B<br>2' - 3' | C<br>2' + 3" | D<br>2' - 3"  | B - D   | XZ    | A - C   | YZ      | B + D | (—)     | A + C   | XY    |
| 0.0          | +2.8         | -0.5         | -2.3          | +5.1    | +7.29 | +0.5    | +1.24   | +0.5  | +2.26   | -0.5    | -1.97 |
| 213'         | (213') + 1'  | 215"         | (213'') + 1"  | B - D   |       | 1' - 1" |         | B + D |         | 1' + 1" |       |
| -2.8         | -2.8         | +1.8         | +2.3          | -5.1    | +7.29 | -0.5    | +1.24   | -0.5  | +2.26   | +0.5    | -1.97 |
| Stat. No.    | 128          |              | Full Values   |         | +7.29 |         | +1.24   |       | +2.26   |         | -1.97 |
| Date         | 2:20.26      |              | Terr. Effects |         | -0.30 |         | +0.43   |       | -2.23   |         | +1.13 |
| Obs. by      | C. B. H.     |              | Topog. Values |         | +7.59 |         | +0.81   |       | +4.49   |         | -3.10 |
| Check. by    | F. L. B.     |              | Norm. Values  |         | +7.00 |         | -1.00   |       | +7.70   |         | +1.00 |
| Anomalies    | R            | 0.8          | $\lambda$     | -34.1   | +0.59 |         | +1.81   |       | -3.21   |         | -4.10 |

FIG. 2

The anomaly of gravity due to the subsurface is then found by algebraic subtraction of the terrain effects from the full observed gradient.

#### TRANSPORTATION

Because of the constant moving of the instrument from one point to another, the problem of transportation is an important one. The

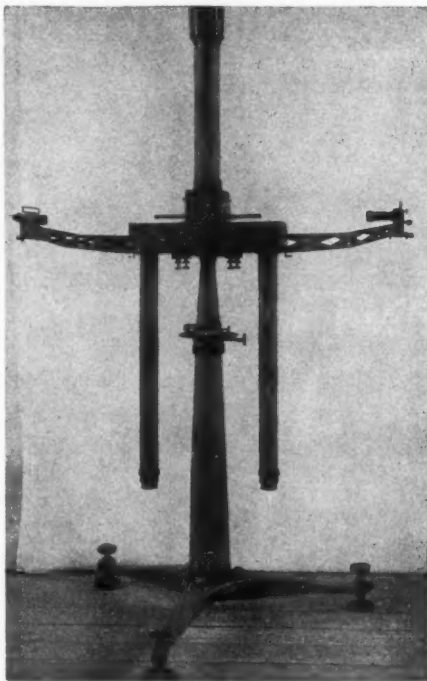


FIG. 3

less personnel and equipment, the faster the outfit can be moved; therefore the greater efficiency. Each company using the torsion balance has developed a system of its own, adapted to particular circumstances.

The large type of instrument, illustrated in Figure 3, is operated by three men: one chief of party, one assistant, and one helper. The outfit used by the writer consists of two  $\frac{3}{4}$ -ton trucks, one of which

carries the instrument and serves as sleeping quarters for two men; the other pulls the house on a trailer and serves as sleeping quarters



FIG. 4



FIG. 5

for the third man and also as a means of communication with headquarters (Figs. 4 and 5).

The whole outfit for the small-type instrument consists of one

truck. The personnel is reduced to two men and the maximum portability with the present type of instrument is almost reached. Figure 6 illustrates the small type of torsion balance, and Figures 7 and 8 show the instrument ready to be moved.

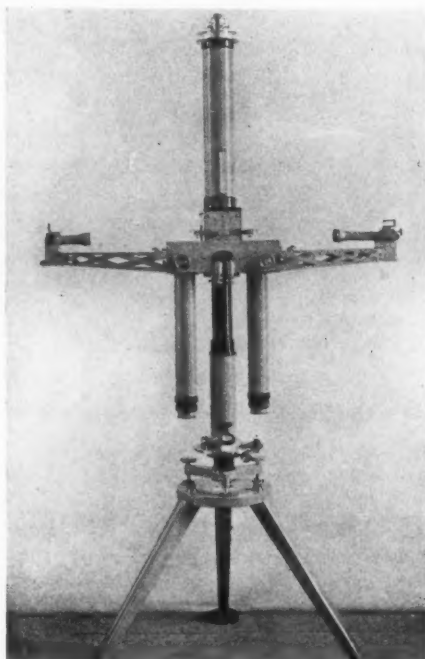


FIG. 6

#### INTERPRETATION OF THE REACTIONS OF THE TORSION BALANCE

The principle of the problem of interpretation can be briefly summarized: Increasing steepness of the gradient indicates approach toward a relatively heavy mass rising toward the surface into relatively lighter rocks; the steeper the gradient, the relatively heavier is the mass, the steeper is the inclination of its flank, or the closer it is to the surface. The gradient is toward the heavier mass, that is, gravity increases toward the heavier mass. This simple principle,

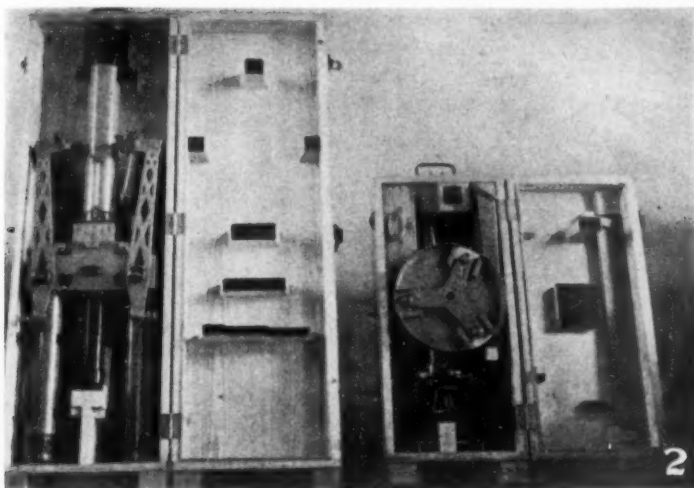


FIG. 7



FIG. 8

however, may be complicated by the immensely varied conditions of the subsurface.

Let us suppose the presence, underground, of a dome, of greater density than that of the surrounding strata, and let us see how it will be revealed by the torsion balance. As defined in the foregoing principles, the gradients must be toward the dome, and their magnitude must be the greater, the steeper the flanks of the dome and the nearer its top to the surface. According to the principle, there must be a reversal of the direction of the arrows<sup>1</sup> on opposite sides of the dome. From this it follows, in the case of a dome, that gradients must be toward the dome; they must increase in magnitude toward it; they must be zero on the top, and must have a reversed direction over opposite sides of the dome. The gradients should be the greatest practically at the edge of the dome. In the case of a lighter mass, such as salt, the gradients must point away from the dome. The salt domes of the Gulf Coast possess a heavy cap rock that neutralizes the effect of the salt and gives gradients pointing toward the dome.

This case is illustrated in Figure 9 by the torsion-balance survey of a typical salt dome in Texas.

This dome is known as a medium deep dome. Its cap rock, consisting of anhydrite, gypsum, and limestone, has a maximum thickness of 800 feet and is nearest the surface at a depth of about 350 feet.

The torsion-balance survey at this dome was made to test the instrument, and not to test the dome. This accounts for the scarcity of stations and the great distances between them. Two cross-sections, *A-A* and *B-B*, have been made with stations half a mile apart. Conditions along these sections are alike.

On the line *A-A*, at Station 509, the gradient is very small, but is already under the influence of the dome, though at least two miles distant from its center. Station 510 shows a definite increase, and Station 511 can be taken as the first to be above the dome. Station

<sup>1</sup>On torsion-balance maps the gradient at a station is represented by an arrow flying in the direction of the increase of the value of gravity, and with a length proportional to the magnitude of the gradient. In torsion-balance work we think more or less in terms of those arrows.

512 shows a decrease of the gradient which is due to the flattening of the cap rock, and 505 shows the approximate location where the gradient should be zero.

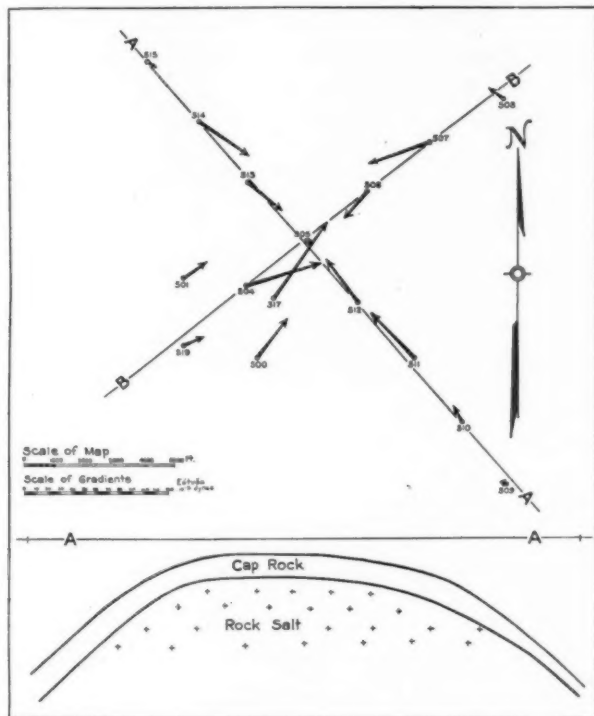


FIG. 9.—Anomalies of gravity at a typical dome in Texas

Station 513 shows the characteristic reversal of the gradients above a dome. Station 514 has the same direction as 513, but, due to the steeper dip of the flank of the dome, is of a larger size. Station 515 shows, as is expected, a very marked decrease.

The conditions are identical along section *B-B* or at any section that could possibly be made. Stations 500, 501, and 517 prove that the gradients anywhere on a dome must follow the principles out-

lined in the beginning. The interpretation of the conditions of the subsurface at this dome has been inferred from the results of the torsion-balance survey exclusively. The correctness of interpretation is proved by the logs of wells drilled there.

The conditions of gravity for a shallow dome in Texas are different, but follow the same principles. The highest point of the cap on this dome is about 100 feet from the surface, and it reaches a depth of 1,500–2,000 feet. It is obvious that such a heavy mass so near to the surface must have an enormous influence on the torsion balance. The map, Figure 10, shows this fact. The arrows crossing each other do not have any particular meaning, but only show that the topographical scale was chosen too small for this case. There is, however, a difference between the two domes. On the dome of Figure 9 the cap rock dips with the salt plug, that is, covers its sides, while on the dome of Figure 10 the cap rock is only on the top of the salt. The sides of this dome are much steeper than the sides of the dome illustrated in Figure 9. This is another explanation of the large difference between the magnitude of the gradients.

The purpose of this survey was the same as for the dome of Figure 9. Although more stations are shown, they are nevertheless half a mile apart. Two cross-sections have been made here also, and a number of extra stations have been added for experimental purposes.

Another difference between the two surveys lies in the fact that in one all gradients point toward the dome, but in the other a number of gradients point away from the dome. Stations 351, 359, and 361 show the attraction of the dome, while 324, 341, 358, 314, 319, and 354 are near or above the edge of the dome, which is dipping more on the west, southwest, and northeast sides than on the east side. Stations 324 and 319, also 358 and 354, illustrate the law that gradients point toward each other above a dome. Station 353 gives an idea about where the point of no gradient must lie. Stations 334, 325, 317, 309, 360, 312, 356, and 335 point away from the dome. This is due in a number of the stations to the normal dip of the subsurface around the dome, and in others, to the salt which is not covered by cap rock. Station 320 shows "gravity normal," which means that the instrument did not register an anomaly. Such zero points must

exist between all points having gradients of opposed or reversed directions, but station 320 was the only such point where an observation happened to be made.

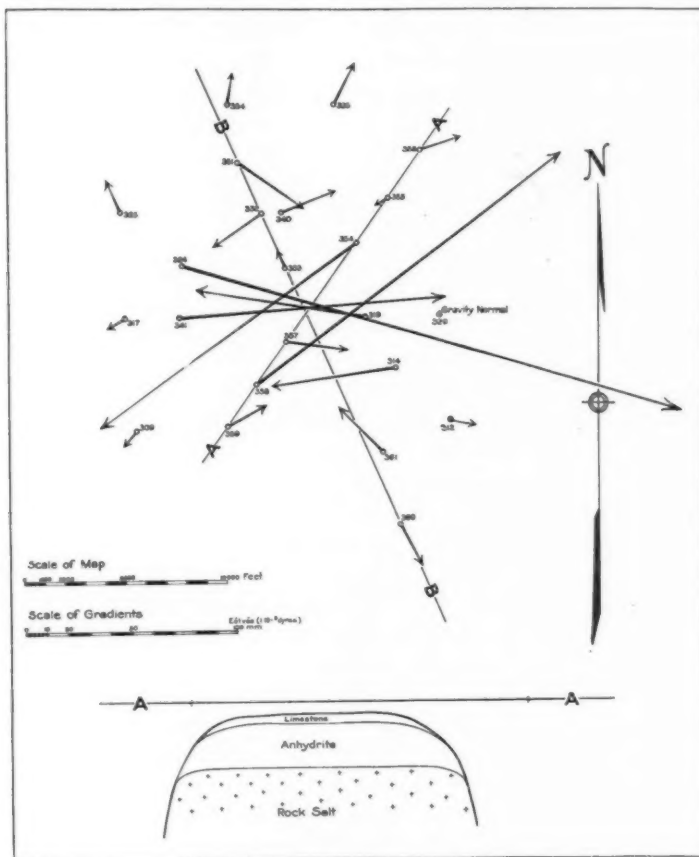


FIG. 10.—Anomalies of gravity at a shallow dome in Texas

A very curious situation is revealed at the points 352 and 340. All expectations indicated a large gradient at 352, similar to that at 324, but the gradient became small in comparison and turned at

right angles to the direction expected. Station 340 was observed for check and gave another surprise in a comparatively small northeast gradient. Several theories could be advanced for this situation, but a few more stations would solve the problem. Theories that the cap rock is deeper, or has an embayment, or is missing between 352 and 354, are very well founded, but none of them could be proved by two stations alone.<sup>1</sup>

From these typical examples it is seen that a dome is indicated by gradients of opposed or reversed direction. Conditions are similar on an anticline because the gradients on its sides must be directed toward the axis, and consequently opposed to each other. In case of an ideal fault, however, conditions are different. The gradients follow the rise or fall of the subsurface, but do not appear as reversals. They show rather the great difference in the intensity of gravity on the up-throw, compared with the down-throw, side of a fault.

Figure 11 illustrates a series of possible folds and faults in Texas discovered by the torsion balance and interpreted from torsion-balance showings, but not yet proved by drilling. Proceeding from northeast to southwest, the subsurface begins to fold at 635. An anticline is marked between 635 and 633, and a syncline is between 633 and 632. A second anticline appears between 632 and 602, and the first fault is indicated between 602 and 603. This fault has been followed up at 622 and 621, then at 623 and 624, at 625 and 626, at 627 and 628, at 629 and 630 and 632; the stations with even numbers are on the up-throw, and those with odd numbers are on the down-throw, side of the fault. A second fault can be seen between 606 and 607 and between 616 and 617. A third fault is located between 610 and 611. The amount of the total faulting is marked by the total difference in the magnitude of the gradient of 602 as compared with that of 611.

These three schematic examples, Figures 9, 10, and 11, illustrate the three most common conditions in that region of the oil country. It should not be understood, however, that all dome and fault structures are shown in such an ideal way. The subsurface may have a

<sup>1</sup> This interpretation has been derived purely from torsion-balance showings, and its accuracy has also been proved by well logs.



tion of anticlinal structure or doming. This bears out the theory that the Powell fault is of secondary origin and followed folding. The horizontal directing lines, or *R* lines, are at right angles to the fault

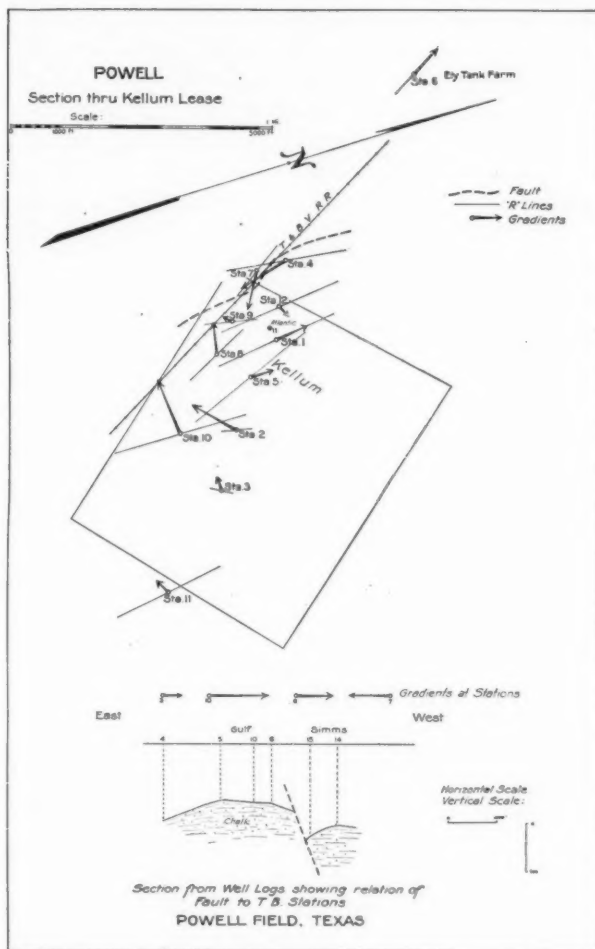


FIG. 12

on the down-throw side and are parallel to the fault on the up-throw side, showing that it is a fault, and not a simple fold.

From Figure 12 it will be noticed that the fault zone exists between stations 6-7 and stations 8-9-1, with probably an offshot between stations 4 and 12 and another between stations 7 and 4. It is known that this fault makes a bend at this place, and several small faults probably occur tangential to this curve.

Figure 12 shows a cross-section of the Austin chalk, drawn from well logs; proves that folding did occur, and gives an explanation of the reversals obtained instead of the normal types of fault gradients. In other parts of this field types of gradients similar to these are found as well as the normal types, showing that the strong folding was not uniformly developed throughout.

These last results are part of a survey of this district made and interpreted by John Moir for the Atlantic Oil Company, to whom the writer is indebted for permission to use them.

The interpretation of the results of the torsion balance calls for much experience in this work and for a knowledge of local conditions and possibilities. It is unfortunate that co-operation, which means so much in this science, is lacking entirely among the different companies. At the present time all companies using the torsion balance do more or less costly experimenting independently, though an exchange of ideas and results would greatly advance the practical usefulness of this instrument.

The writer expresses his belief that more co-operation will be a common practice in the near future.

#### DISCUSSION

F. B. PLUMMER: It is not necessary to take extreme care in orienting the torsion balance. An ordinary compass needle is placed on the instrument and the balance arms turned north and south. There is on the instrument an arc graduated into degrees. From north position the balance is turned into the 120-degree position on the arc, and then to the 240-degree position, so that the rotation is easily carried out.

## OIL AND GAS PROSPECTS OF NEW ZEALAND<sup>1</sup>

FREDERICK G. CLAPP<sup>2</sup>

### ABSTRACT

Oil has been known in New Zealand for many decades. About 60,000 barrels have been marketed in the past in Taranaki provincial district in the western part of North Island; a few barrels have been taken out of the East Coast of the same Island; and about 800 barrels marketed from the Westland district of South Island. Intensive drilling has taken place only in the immediate vicinity of New Plymouth, in Taranaki district, but some wildcatting was done on the East Coast (mostly in unfavorable localities geologically), and a few shallow holes have been sunk in Westland and elsewhere. All parts of New Zealand are considered unimportant as regards oil prospects, except Westland, Taranaki, and East Coast, of which the last-mentioned area appears the most favorable. Operations are now being undertaken by Taranaki Oil Fields Ltd. in Taranaki and East Coast districts, where fundamentally favorable geologic conditions exist, including seepages, competent source rocks, reservoir beds, cover, and a satisfactory stage of metamorphism. Whether either district will result in the discovery of commercial oil or gas fields remains to be seen.

### INTRODUCTORY STATEMENT

In recent years New Zealand has not been conspicuous in petroleum literature. By going back through three-quarters of a century, however, one finds several periods during which oil men looked to New Zealand as a prospective producing field. Intermitent periods of excitement in Taranaki Province (Fig. 1) culminated from the type of optimism which generally determines whether a country is to be productive or barren. During these periods as many as thirty holes were drilled to depths ranging from 1,000 to 5,680 feet, and a number of semi-commercial wells were obtained.

Nevertheless, New Zealand has not yet become a profitable field. A refinery at New Plymouth—the chief city of Taranaki district—was purchased by the Anglo-Persian Oil Company and dismantled, parts of the plant being used in a refinery for Persian crude since built at Melbourne, Australia, and New Zealanders gradually were led to believe that their country was not petroliferous. Let us

<sup>1</sup> Published with the permission of Taranaki Oil Fields Ltd., Melbourne, Australia.

<sup>2</sup> Consulting geologist and petroleum engineer, 50 Church Street, New York City.

analyze the situation from a national point of view to ascertain whether that conclusion is justified.

#### INVESTIGATIONS TO DATE

Studying the situation early in 1924, the writer concluded that conditions had never been adequately investigated. Some geological work had been done previous to the first Taranaki boom, but the names of men known to the oil world were conspicuous by their absence. As a matter of fact, little knowledge of refined oil geology existed anywhere at that time and its absence in New Zealand is not surprising.

Some excellent work has been done by the New Zealand Geological Survey under the leadership of such men as Alexander McKay, Sir James Hector, J. Mackintosh Bell, and finally by the present government geologist, Percy G. Morgan. Reports have been issued by that Survey on all parts of the Dominion, with special reference to mining gold, the most valuable mineral that New Zealand has produced commercially. Good geologic maps in bulletin form on a scale of a mile to an inch are appearing at intervals, and in time the entire Dominion will be mapped in Survey districts 12 miles square, each composed normally of sixteen blocks,  $2\frac{1}{2}$  miles on each side. Little was said about oil in these bulletins because interest in oil was not sufficient to justify concentrating on it, but several of the bulletins contain notable oil predictions and descriptions valuable to an oil man.

Practically the only geologist familiar with oil fields who visited New Zealand prior to 1923 was Dr. J. Wanner, employed only on special rapid reconnaissance work for the "Shell" Company. He did not make exact locations for the test wells drilled by the company he represented. On one or two occasions in recent years other geologists have visited New Zealand for oil interests, but these men were apparently given time only to reconnoiter a field and continue to the next one. Wanner's report is the only one, aside from government reports, which has been available, and this report confined attention largely to Hawkes Bay district, in which his company was chiefly interested. The writer of the present paper has, however, been given time for far-reaching studies, owing to the wise policy



FIG. 1.—Map of New Zealand showing areas discussed in this paper

of his clients, and has had the valuable geologic assistance of Ernest Marquardt, Chester W. Washburne, Paul B. Whitney, W. Dana Miller, Edwin H. Hunt, G. D. Osborne, and E. O. Macpherson, to all of whom he would cordially express his appreciation. He wishes in particular to express his thanks and appreciation to Mr. Percy G. Morgan, government geologist, for revising the columnar sections herein included, bringing them into accordance with the nomenclature, etc., accepted by the New Zealand Geological Survey.

#### GENERAL PHYSICAL AND GEOLOGIC DESCRIPTION

New Zealand in general is mountainous, with several notable exceptions, among which are the Canterbury plains in the eastern part of South Island and the rolling country of Western Taranaki in the western part of North Island. The discussion of oil prospects in New Zealand has little relation to topographic characteristics of the Dominion as a whole. The country is one of many contrasts, ranging from barren plateaus of volcanic ash occupying the center of North Island to the rich pastures of Taranaki and Canterbury, which constitute some of the choicest dairy lands in the world. The climate varies from semitropical in North Auckland peninsula to the cold winters of Stewart Island in the extreme south. Volcanoes in the Bay of Plenty and in the center of North Island are in marked contrast to great living glaciers in the Southern Alps, and the broad Canterbury plains are contrasted to deep and inaccessible fiords in the southwest portion of South Island. Above all, New Zealand is an agreeable and prosperous country, from which the chief exports are wool and dairy products. Gold once ranked high as a product of the earth, but the vast placers are now almost deserted.

The strata range in age from pre-Ordovician to Recent, the country having Paleozoic, Mesozoic, and Tertiary strata. It is believed that the pre-Cretaceous strata are everywhere too much metamorphosed to contain oil. They possess attitudes of generally great structural complexity, and appear worthy of note here solely because they form the main backbone of South and North Islands and because several more recent sedimentary areas lie in obvious relations to their controlling axis.

New Zealand is so far removed from geologic provinces of the

rest of the world that its able geologists have evolved a system of nomenclature which is entirely their own. The principal subdivisions are given here in terms of their North American equivalents as closely as known. Unconformities are not specified in this table (Table I), for they are very plentiful in New Zealand.

TABLE I\*  
GENERALIZED GEOLOGIC COLUMN FOR NEW ZEALAND

| System     | Period                  | American Equivalent      | Maximum Thickness (Feet) | Description   |
|------------|-------------------------|--------------------------|--------------------------|---|
| Quaternary | Recent                  | Recent                   | 100                      | Coastal, valley, lake, spring, glacial, and volcanic deposits             |
|            | Pleistocene             | Pleistocene              | 1,000+                   | Gravels, sands, tills, tuffs, etc.  |
| Wanganui   | Castle Cliff Waitotara  | Pliocene                 | 6,000+                   | Limestone, sandstone, clay, shale, pumice, and glacial deposits           |
| Karamea    | Oamaru                  | Miocene† and Oligocene   | 10,000+                  | Limestone, sandstone, greensands, clay, shale, and tuffs                  |
|            | Waimangaroa             | Eocene                   | 2,300                    | Sandstone, shales, coals, and conglomerates                               |
| Amuri      | Waipara                 | Cretaceous‡              | 12,000+                  | Limestone, sandstone, shales, marls, coals, and conglomerates             |
| Hokonui    | Mataura                 | Jurassic                 | 13,000                   | (Uppermost metamorphic rocks) Sandstones, basalts, shales, and thin coals |
|            | Putataka                |                          |                          |   |
|            | Otapiri                 | Upper Triassic           | 5,000                    | Sandstones and shales   |
|            | Wairoa                  |                          |                          | Sandstones and shales with boulder bed at base                            |
|            | Kaihiku                 | Lower Triassic           | 4,000                    | Shales and sandstones   |
|            | Aorangi                 | Permian (?)              | 4,000                    | Sandstones and slaty shales   |
| Te Anau    | Maitai Te Anau          | Carboniferous or Permian | 7,000—12,000             | Slaty shales, sandstones, greenstones, etc.                               |
| Manapouri  | Wangapeka (Baton River) | Siluro-Devonian§         | 20,000+                  | Slaty shales, sandstones, limestones, and quartzites                      |
|            | Kakanui (Aore)re        | Ordovician               |                          | Metamorphic shales, sandstones, and schists                               |
|            | Maniototo               | Cambrian(?)              | 26,000                   | Gneisses and schists  |

\* In preparation of this and later tables the writer has made use of Professor James Park's *The Geology of New Zealand* (Wellington, 1910, 488 pages; 161 illus.), and Professor P. Marshall's *Geology of New Zealand* (Wellington, 1912, 218 pages; 114 illus.). The first-mentioned is the one generally followed herein.

† Yields oil and gas seepages in Taranaki, Westland, and East Coast districts.

‡ Yields oil and gas seepages in East Coast district.

§ Probably Devonian; but perhaps Silurian in part.

#### DISTRICTS CONSIDERED

On account of their metamorphism, all pre-Cretaceous rocks in New Zealand are believed unworthy of consideration from the

standpoint of oil. Hence, the rocks that may contain oil are of Cretaceous and later ages. By outlining areas of rocks of these ages one can eliminate practically all the obviously unfavorable regions. Areas which have been given any consideration are here mentioned in order, commencing with those of least importance and ending with the most promising. Certain areas of little sedimentary importance, which have been given consideration by other investigators, are referred to, thereby covering the essential features of development activities without need for recapitulation and eliminating vast regions.

The areas considered are referred to on the accompanying map by the identical numbers here used.

1. *Vicinity of Invercargill, Southland.*—Miocene and Pliocene deposits of parts of Southland cover an area of about 1,000 square miles, but the evidence seems to be that they are too thin to act as source rocks, to carry containers, and supply sufficient cover, even if suitable structure exists in them. The district has been described by Park,<sup>1</sup> but authentic seepages are not reported and the district is not believed to be important as regards oil prospects.

2. *Canterbury district.*—In the central-eastern part of South Island are about 3,000 square miles, largely consisting at the surface of flat Pleistocene deposits. The presence of oil in them has not been definitely disproved, but numerous water wells exist and none of the surrounding uplands evince obvious conditions that are of importance as regards oil.

At Chertsey, a few miles north of Ashburton, a well was drilled to a depth of 2,170 feet, penetrating 500 or 600 feet of Recent and late Pleistocene gravels forming the Canterbury plains, and, according to Morgan,<sup>2</sup> may have entered late Tertiary deposits. These strata yield a little gas and some black viscid globules of oil at a depth of 1,368 feet. Nothing better has been found in Canterbury.

3. *Marlborough district.*—About 400 square miles of Cretaceous and later rocks exist in the northeastern part of South Island, form-

<sup>1</sup> James Park, "The Geology of the Queenstown Subdivision, Western Otago Division," *New Zealand Mines Department, Geol. Survey Branch Bulletin* 7, 1909.

<sup>2</sup> Percy G. Morgan, *New Zealand Journal of Science and Technology*, Vol. 7, No. 5 (1925), p. 289.

ing narrow belts parallel to the coast, but much broken up, apparently constituting an extension of the great Cretaceous area which exists in the eastern side of North Island. Gas and oil seepages were reported years ago at Benmore by McKay<sup>1</sup> and Thomson,<sup>2</sup> at Cheviot by Morgan,<sup>3</sup> and at Puhipahi, and a small seepage 3 miles north-east of Ward, by Morgan.<sup>4</sup> The last-mentioned seepage turned out to be only one square yard of hard sandy rock stained brown by oil and possibly of Jurassic age, indicating that the oil may have entered from some more recent formation. The few seepages of Marlborough district are believed to show no evidence of coming from strata which lie in structural attitudes such as would probably render them commercially oil-bearing.

4. *North Auckland peninsula*.—Some petroliferous shales are reported in the northern part of Auckland district, and areas of Cretaceous and Miocene beds exist throughout an area of about 5,000 square miles. The presence of structurally favorable conditions there has not been disproved; but the areas are small, much cut by volcanic intrusions, underlain by Jurassic beds in part, and no particular encouragement exists as to the presence of oil in that region.

*Other districts*.—In addition, small and unimportant seepages of amber-colored oil have been reported in peat deposits near Wellington,<sup>5</sup> and also near Waiotapu among the geysers of the central thermal district of North Island, the latter apparently due to the distillation of carbonized wood buried in the underlying tuffs. Only three districts, however, appear worthy of serious discussion. These have already been enumerated by Morgan,<sup>6</sup> and are (5) the

<sup>1</sup> Alexander McKay, "Report of Geological Explorations during 1885," *New Zealand Mines Department, Geol. Survey Branch Bulletin 17* (1886), pp. 86-87.

<sup>2</sup> J. Allan Thomson, "Oil Indications in the Benmore District, East Marlborough," *New Zealand Mines Department, Geol. Survey Branch* (9th Annual Report, N.S., 1915), pp. 100-101.

<sup>3</sup> Percy G. Morgan, *New Zealand Mines Department, Geol. Survey Branch* (10th Annual Report, N.S., 1916), p. 23.

<sup>4</sup> "Oil Seepages Near Ward, Marlborough," *New Zealand Mines Department, Geol. Survey Branch* (15th Annual Report, N.S., 1921), pp. 18-19.

<sup>5</sup> Percy G. Morgan, "Oil Occurrence near Paraparaumu," *New Zealand Mines Department, Geol. Survey Branch* (8th Annual Report, N.S., 1915), Appendix C-2, p. 147.

<sup>6</sup> Percy G. Morgan, "Petroliferous Areas in New Zealand," *New Zealand Journal of Science and Technology*, Vol. VII, No. 5 (1925), pp. 287-90; *Engineering and Mining Journal* (January 31, 1925), pp. 207-8.

Westland-Nelson district, (6) the Taranaki district, and (7) the East Coast district of North Island. In all of these basins Miocene and Pliocene sediments are conspicuous. In the East Coast district the Cretaceous is also prominent, but it was not deposited on the west coast of either North or South Island. The position of the Upper Cretaceous shore line seems to have been coincident with the central axis of the New Zealand islands.

#### 5. WESTLAND-NELSON DISTRICT

*General statement.*—The Greymouth district, on the west coast of South Island, has twice been examined by oil geologists. About 1911 it was visited by Dr. J. Wanner, in the employ of the "Shell" Company, and in 1924 by E. Call Brown, of California, acting for the Kotuku Prospecting Company. At the time of Wanner's visit little information was available, and Call Brown's report is stated by his clients to have been an unfavorable one. A report by the New Zealand Geological Survey<sup>1</sup> gives a detailed areal geologic map of the vicinity of Greymouth and a description of the prospecting at Kotuku up to that date.<sup>2</sup> Other reports exist on the oil indications found there,<sup>3</sup> and government reports have been issued<sup>4</sup> on several small Tertiary areas in the district.

<sup>1</sup> Percy G. Morgan, "The Geology of the Greymouth Subdivision, North Westland," *New Zealand Mines Department, Geol. Survey Branch Bulletin 13* (N.S., 1911), 159 pages, 6 plates, 8 maps, and 3 geol. sections.

<sup>2</sup> *Op. cit.*, pp. 132-49.

<sup>3</sup> Percy G. Morgan, *New Zealand Mines Department, Geol. Survey Branch* (4th Annual Report, N.S., 1910), p. 18; Alex. McKay, "Report on Indications of Petroleum at Deep Creek, Lake Brunner, Nelson," *New Zealand Mines Report C-10* (1901), pp. 3, 10-12; *New Zealand Mines Record*, Vol. 4 (1900-1901), pp. 201-3.

<sup>4</sup> J. M. Bell and Colin Fraser, "The Geology of the Hokitika Sheet, North Westland Quadrangle," *New Zealand Mines Department, Geol. Survey Bulletin 1* (N.S., 1906), 101 pages, 9 maps, 4 geol. secs., and 16 pls.

E. J. H. Webb, "The Geology of the Mount Radiant Subdivision, Westport Division," *New Zealand Mines Department, Geol. Survey Bulletin 11* (N.S., 1910), 46 pages, 4 maps and sections.

J. H. Bell, E. de C. Clarke, and Patrick Marshall, "The Geology of the Dun Mountain Subdivision, Nelson," *New Zealand Mines Department, Geol. Survey Branch Bulletin 12* (N.S., 1911), 70 pages, 4 maps, 6 secs., and 9 pls.

P. G. Morgan and J. A. Bartrum, "The Geology and Mineral Resources of the Buller-Mokihinui Subdivision, Westport Division," *New Zealand Mines Department,*

*General geology.*—In the vicinity of Nelson, in the northern part of South Island, and at intervals southwestward through several intermontane valleys and paralleling the coast from the vicinity of Greymouth southwest to Hokitika are areas that aggregate about 2,500 square miles in which the stratigraphy has at times been considered potentially favorable for oil. The rocks range in age from the Greenland and Alahura series of Paleozoic age, intruded by granites and gneisses, through Miocene to Recent, the section being, roughly, as shown in Table II.

Some fair seepages formerly existed at Kotuku, and shallow wells have tapped oil in small quantities in a shale of unknown age a short distance above the Cobden limestone.

*Favorable and unfavorable conditions.*—Conditions that might have been considered favorable to the occurrence of oil are (a) the presence of prominent seepages on a mild anticline at Kotuku, 13 miles southeast of Greymouth and (b) a past production of about 80 barrels of oil from one shallow well and of about 1,000 barrels from other wells and a shaft at that place. Some of the oil was marketed and used at Greymouth. The writer is indebted to Mr. Charles N. Taylor, of Gisborne, who was manager and one of the property owners, for information as to the drilling at Kotuku.

As opposed to these conditions, the unfavorable ones outweigh those that may be considered favorable and may even vitiate the potentially favorable conditions previously outlined. In the first place, the strata in which the seepages exist are all of Tertiary and Quaternary ages; but at several localities on the Paparoa anticline, 9 miles west of Kotuku, strata of Paleozoic and Eocene ages outcrop, and at coastal localities a few miles north of Greymouth the pre-Tertiary granites are exposed. Only insignificant seepages have been reported in Westland outside the limits of the Kotuku anticline, but oil-smelling limestone has been reported in one locality. Although about 1,100 barrels of oil appear to have been produced

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*Geol. Survey Branch Bulletin 17* (N.S., 1915), 210 pages, 9 maps, 6 secs., 19 pls., and 18 figs.

J. Henderson, "The Geology and Mineral Resources of the Reefton Subdivision, Westport and North Westland Division," *New Zealand Mines Department, Geol. Survey Branch Bulletin 18* (N.S., 1917), 232 pages, 14 maps and plans, 9 pls.

in the aggregate, this is believed by persons associated with the operations to have resulted in a practical draining of the "field."

*Wells drilled at Kotuku.*—Enough test holes were sunk at Kotuku to prove that the oil deposit there is of slight lateral extent and small

TABLE II  
GEOLOGIC COLUMN OF WESTLAND DISTRICT

| Period                 | Series or Formation                 | Thickness (Feet)      | Description   |   |
|------------------------|-------------------------------------|-----------------------|---|---|
| Recent and Pleistocene | Newer fluvial and marine gravels    | 200 +                 | Gravels   |   |
|                        | Older fluvial and marine gravels    |                       |   |   |
|                        | Morainal and fluvio-glacial gravels | 500 +                 | Tills, gravels, and boulders  |   |
|                        | Unconformity                        |                       |   |   |
| Pliocene               | Moutere gravels                     | 700                   | River deposits(?)   |   |
|                        | Unconformity                        |                       |   |   |
| Miocene and Oligocene  | Greymouth                           | Blue Bottom formation | 1,200   | Calcareous blue marine clays            |
|                        |                                     | Cobden limestone      | 1,200 ±   | Limestone                               |
|                        |                                     | Port Elizabeth beds   |   | Marly mudstones                         |
|                        |                                     | Omotumotu beds        | 1,200?  | Sandstones and mudstones                |
| Eocene                 | Coal measures                       | Unconformity          |   |   |
|                        |                                     | Kaiata beds           | 2,000   | Sandstones, shales, and important coals |
|                        |                                     | Island sandstone      | 500   |   |
|                        |                                     | Brunner beds          | 500   |   |
|                        |                                     | Paparoa beds          | 5,000 ±   |   |
|                        | Unconformity                        |                       |   |   |
| Paleozoic              | Greenland and Arahura series        | 25,000 +              | Greywackes, argillites, quartz and mica schists, gneisses, slates, etc. |   |

production. The discovery was made in 1897 by Nils Mortensen (a Scandinavian) and Giacomo Dentella (an Italian), who organized the first developments. Mr. William Cooper, of Gisborne, became interested and pegged out a 650-acre lease for the Lake Brunner Oil Company and imported a primitive drilling plant. The lease was then acquired by the Kotuku Consolidated Oil Company (composed

of Greymouth people), which drilled nine holes. These wells ranged from 104 to 871 feet deep and passed through a petroliferous shale above the Cobden limestone (Middle Miocene) at depths ranging from 400 to 500 feet. The Kotuku Oil Syndicate, composed of Joseph and Charles N. Taylor, of Greymouth, and others, drilled 15 holes to depths ranging from 80 to 400 feet and sank a shaft 83 feet by hand. Between 1910 and 1914 the Kotuku properties were acquired by the Kotuku Oilfields Syndicate, a subsidiary of the "Shell" Company, and two holes were drilled, reaching slate below the Cobden limestone at 650 to 800 feet from the surface. In 1920 the Kotuku Prospecting Company, consisting of a Mr. Davis, of Australia, a Mr. McCrea, of California, and others, drilled two holes and reached Paleozoic slates at 950 and 1,175 feet, respectively. No holes deeper than this last have ever been drilled in the Kotuku "field," and conditions do not warrant deeper drilling, as the underlying rocks are too old and metamorphosed to be petroliferous. The drilling at Kotuku may be said to have been exhaustive and to have disposed of the probability of a commercial field in that particular locality.

Deeper holes have been drilled in Westland, as the No. 3 "bore" hole<sup>1</sup> on land of the Greymouth Harbor Board near Dobson, which attained a depth of 2,165 feet, and the No. 4 "bore" hole<sup>2</sup> on the state coal reserve, which was 1,453 feet deep; but these were drilled for coal.

#### 6. TARANAKI DISTRICT

*General statement.*—The sedimentary area in Taranaki district is largely coincident with the broad rolling plains of the same name covering the greater part of the peninsula which culminates in Mount Egmont in the western part of North Island. These plains extend east to Waitara River in the northern, and Wanganui and Maniwatu rivers in the southern part of the basin, and the area includes the difficultly accessible "back blocks" as far east as the volcanoes of Ruapehu, Ngauruhoe, and Tongariro on the ash-strewn plateaus of central New Zealand. The geology of the north-

<sup>1</sup> Morgan, *op. cit.*, p. 130.

<sup>2</sup> *Ibid.*, p. 128.

western part of this area has been mapped and described by Clarke,<sup>1</sup> and that of the northeastern part by Henderson and Ongley.<sup>2</sup>

Taranaki district may be considered as generally occupying the east half of a great geosyncline, the west half of which lies beneath the Tasman Sea. The basin is bounded in northeastern Taranaki and in Auckland district by formations of Jura-Trias age. The strata dip generally west and southwest, so that formations that are high in the mountains of northeastern and eastern Taranaki and northern Wellington district attain great depths in the vicinity of New Plymouth.

In the Taranaki sedimentary basin the rocks are of Miocene and Pliocene ages. They lie nearly flat, are soft and unconsolidated, and have been subjected to no metamorphism sufficient to distil away, and to no breaking sufficient to allow to escape, any petroleum that may have existed, as is proved by the existence of petroleum at least in semicommercial quantity.

Although no oil was found from the immediate vicinity of New Plymouth, excellent showings of gas were discovered 5 miles south of New Plymouth and in wells near Inglewood, about 10 miles southeast of New Plymouth. Many gas vents exist south of New Plymouth and east of Inglewood; and evidence exists that a large area is potentially favorable, subject to the occurrence of suitable structure, porous interbedded sands, and a competent source of origin. The strata dip normally  $1^{\circ}$ – $5^{\circ}$  SW. The everpresent Miocene and Pliocene clays are thousands of feet thick in western Taranaki, serving as an ideal cover for any existing oil or gas. Sandy outcrops in central and eastern Taranaki and sandy clays in several horizons at New Plymouth indicate that suitable sands exist.

*Stratigraphy.*—The rock formations of Taranaki district are pre-vaillingly Miocene and Pliocene and may be represented by the section shown in Table III.

<sup>1</sup> Edward de Courcy Clarke, "The Geology of the New Plymouth Subdivision, Taranaki Division," *New Zealand Mines Department, Geol. Survey Branch Bulletin 14* (N.S., 1912), 58 pages, 5 maps, and a well-record sheet.

<sup>2</sup> J. Henderson and M. Ongley, "The Geology of the Mokau Subdivision, etc.," *New Zealand Mines Department, Geol. Survey Branch Bulletin 24* (N.S., 1923), 83 pages, 4 plates, 6 maps, and sections.

*Geologic structure.*—Two types of abnormal structure exist in Taranaki, namely, (1) intrusive plugs of post-Miocene andesite-porphry, and (2) arrested and reverse dips discovered in a few

TABLE III  
GEOLOGIC COLUMN IN TARANAKI DISTRICT

| Period                         | Series or Formation  | Thickness (Feet) | Description   |   |
|--------------------------------|----------------------|------------------|---|---|
| Recent and Upper Pleistocene   | Recent               | 0-100            | Marine, eolian, and alluvial deposits of gravel, mud, and sand              |   |
|                                | Upper Pouakai series | 0-200            | Andesites, tuffs, and agglomerates  |   |
| Lower Pleistocene and Pliocene | Unconformity (?)     |                  |   |   |
|                                | Lower Pouakai series | 0-600            | Agglomerates, tuffs, and intrusions of Sugar Loaf Islands and Pouakai range |   |
|                                | Unconformity         |                  |   |   |
|                                | Waitotara beds*      | 2,000            | Clays and marls, shelly limestones, and conglomerates                       |   |
| ?                              |                      |                  |   |   |
| Miocene                        | Oneiro Series        | Urenui beds      | 2,700   | Clays and thin sands; conglomerate                        |
|                                |                      | Tongaporutu      | 1,400   | Clays and sandstones                                      |
|                                |                      | Mohakatino       | 600-800   | Clays, sandstones and limestones, and Whareorino andesite |
|                                |                      | Unconformity (?) |   |   |
|                                |                      | Mokau            | 1,700   | Clays, sandstones, limestones, and coals                  |
|                                | Mahoenui series†     |                  | 600   | Clay, limestone, and sandstone                            |
|                                | Unconformity         |                  |   |   |
|                                | Te Kuiti†            |                  | 400(?)  | Limestone, sandstone, shale, and coal                     |
|                                | Great Unconformity   |                  |   |   |
| Jura-Trias                     | Hokonui system, etc. | †                | Greywackes, argillites, etc.  |   |

\* Part of Wanganui system. Outside of Taranaki the Waitotara beds are as much as 3,250 feet thick.

† Do not crop out in Taranaki.

localities by the writer, Ernest Marquardt, and G. D. Osborne, and mapped in detail by Marquardt, P. B. Whitney, and Edwin H. Hunt, assisted by F. M. Cole and E. E. Leach.

The greatest mass of intrusive andesite is Mount Egmont (altitude 8,260 feet and diameter 12 miles). Smaller intrusive masses, prominent in the topography of western Taranaki, are the so-called "Sugar Loaf Islands" at Moturoa, New Plymouth, and several hills south of the city. Several areas, one forming the so-called "uplift" about 7 miles south of New Plymouth, another surrounding the town of Inglewood, and others south and west of Mount Egmont, are conspicuous in the landscape as "conical hills," which exist by hundreds.

Within a score of miles from Mount Egmont the rolling plains consist at the surface, and to a depth of scores or hundreds of feet, of coarse andesitic tuffs and agglomerates, in some places fine and pumiceous, in others containing boulders a score of feet in diameter. The roots of some of these conical hills have been studied on the coast at New Plymouth and in roadside and stream cuts, and they are found to be miniature centers of volcanic eruption. Similar phenomena were observed on the central ashstrewn plateaus northwest of Mount Tongariro and on similar plateaus between Rotorua and Cambridge in Auckland district. The best wells in Taranaki were obtained a few hundred feet east of the Moturoa andesite intrusion.

The surface of western Taranaki is so thickly covered by Pouakai agglomerate and later deposits of no consistent structural attitude that any estimate of the form of the underlying rock structure is generally impossible. On the other hand, eastward from Waitara, Inglewood, Stratford, and Hawera, a great many dips have been measured.

Nothing has been published on the sedimentary structures of Taranaki and nothing was known of them until recently, which accounts for the concentration of drilling at New Plymouth up to this time. Vast areas of Taranaki are so ash-covered, or forested, that no structure can be determined. Anticlines, domes, and terraces with reverse dips ranging from  $5^{\circ}$  to  $15^{\circ}$  have been found, however, at several places in central Taranaki and are under lease by the Taranaki Oil Fields Ltd.

*Summary of prospects.*—Owing to the fact that the only known Taranaki oil field is situated on a normal dip within a few hundred

feet of an igneous intrusion, local geologists have been inclined to consider the oil as being a product of distillation caused by volcanic action. It is probable, however, that stresses sufficient to produce the folds of central Taranaki are competent to produce oil without the aid of igneous heat. Numerous coals in the Mokau series, fossiliferous beds at many Miocene and Pliocene horizons, and the uniformly marine clays attest the existence of a competent source of origin. The existence of porous sand beds has been proved. Oil fields may be expected, therefore, in Taranaki at points where structure and containers coincide, or possibly even on the normal dip in lenticular sands or tuffs, or at igneous contacts.

*Developments to date.*—The presence of oil seepages in the sea near the Sugar Loaf Islands and New Plymouth Breakwater was known to the natives before the advent of Europeans and their presence was noted by Dieffenbach<sup>1</sup> in 1839. The most complete account of drilling activity up to 1912 is given by Clarke,<sup>2</sup> but later reports of the same department<sup>3</sup> supply the history of operations from 1912 to the present date. A popular account, written from the journalistic viewpoint, but containing most of the noteworthy facts from the time of the discovery of oil until 1911, was given by Henry.<sup>4</sup>

Drilling in Taranaki commenced in 1865, at the head of New Plymouth breakwater, and five rather distinct periods of activity ensued. From 1865 to 1868 several wells only a few hundred feet deep were sunk in the vicinity of the breakwater seepages, and some oil was found. The second period commenced about 1889 and lasted until 1900, during which time several wells were drilled in less than half-a-mile radius directly east of the original shallow

<sup>1</sup> E. Dieffenbach, *Travels in New Zealand*, Vol. 1 (1843), pp. 134-35.

<sup>2</sup> Edward de Courcy Clarke, *op. cit.*, pp. 30-37.

<sup>3</sup> J. M. Bell, "Preliminary Report on the Taranaki Oilfield," *Journal of New Zealand Council*, C-14 (1909), pp. 1-8; *Petroleum Review* (May 21 and June 4, 1910), 31 pages. Sir James Hector, *Report on the Petroleum Found at Taranaki*, June 18, 1866.

Alexander McKay, "Report on Petroleum at New Plymouth, Taranaki," *Journal of New Zealand Council*, C-9A (September 2, 1898), pp. 3-10; 2 maps.

Percy G. Morgan, "The Taranaki Oilfield," *New Zealand Mines Department, Geol. Survey Branch* (8th Annual Report, N.S., 1914), Appendix C, pp. 117-70; "New Plymouth Oil Field," *New Zealand Mines Department, Geol. Survey Branch* (9th Annual Report, N.S., 1915), Appendix C, p. 95.

<sup>4</sup> J. D. Henry, *Oilfields of New Zealand* (London, 1911), pp. 1-180; 23 illus.

holes. The greatest depth reached at that time was about 2,000 feet. Again a lull occurred, but from 1906 to 1912 the wells were deepened, and at a point between 2,100 and 2,300 feet they obtained semicommercial deposits of oil. Some oil still flows from these wells at approximate weekly intervals.

During a more recent period of activity several wells were deepened to more than 3,000 feet, finding the best flow of oil at about 3,100 feet. One well was then drilled to 5,680 feet, after finding the usual deposits of oil between 2,100 and 2,200 feet. According to the New Zealand Mines Department<sup>1</sup> over 60,000 barrels gross production were marketed. The wells obtained no additional production of importance below 3,200 feet, although excellent showings were found below 5,000 feet, and thick carbonaceous and bituminous clays and shales were encountered.

The most recent period of activity commenced in 1924, when Taranaki Oil Fields Ltd. started a new test near the old shallow wells at the breakwater. This well penetrated several sands having good showings of gas and oil, and at 1,555 feet it encountered about 6,000,000 cubic feet a day of non-combustible gas with a rock pressure of 625 pounds a square inch. The hole was abandoned at 4,360 feet. Another test by the same company was drilled on a structural terrace at Tarata, 15 miles east of New Plymouth, reaching a depth of 5,010 feet without favorable result.

Nearly all of these wells were situated within half a mile of the breakwater at Moturoa at the western end of New Plymouth municipality, and all of the Taranaki production was obtained in this area. Several tests, however, were made on the southern outskirts of New Plymouth; two holes were drilled between New Plymouth and Waitara; two holes, near Inglewood, 10 miles southeast of New Plymouth; and one hole was drilled at Huiroa, 16 miles southeast of Inglewood or 26 miles southeast of New Plymouth. Table IV gives a concise statement of the wells drilled in Taranaki.

*Analyses of gas and oil.*—Aside from the gas in the Moturoa wells, gases of Taranaki have the compositions given in Table V. Gases from the Moturoa wells are quite different from Table V in composition, as shown in Table VI. Plenty of oil analyses exist. Table VII

<sup>1</sup> Personal communication.

is of a sample collected by the writer from well No. 3, of Taranaki Petroleum Company.

TABLE IV\*  
WELLS DRILLED IN TARANAKI DISTRICT

| No.   | Name of Well   | Date Completed | Total Depth (Feet) | Result   |
|-------|--|----------------|--------------------|--|
| 1...  | "Alpha" (or "Oil or London"); Carter <i>et al.</i> (Sold to Tar. Petrol. Co.)  | 1867           | 180                | 3 bbls. per day  |
| 2...  | Well "No. 1," Taranaki Petrol. Co.   | 1866           | 310                |  |
| 3...  | Well "No. 2," Taranaki Petrol. Co.   | 1866           | 318                |  |
| 4...  | "Victoria" (or "Oil or Dublin"), Peoples Petrol. Co.                           | 1867           | 516                |  |
| 5...  | "Beta" (or "Oil or Edinburgh"); Taranaki Petrol. Co.                           | 1868           | 684                | 1½ bbls. in 12 hrs.  |
| 6...  | Booth's; N.Z.P. & I. Syndicate and Samuels Syndicate                           | 1891           | 930                | 4 bbls. per day  |
| 7...  | Samuels No. 2, Samuels Syndicate   | 1891           | 1,100              | 10 bbls. per day   |
| 8...  | Mace's, Herekawe, or Samuels No. 3; Samuels Syndicate                          | 1895           | 1,354              | Dry  |
| 9...  | Putt's, or Samuels No. 5; Samuels Syndicate                                    | 1898           | 2,053              | Prod., 8,600 bbls., 1912-15  |
| 10... | Okey's, or Samuels No. 6; Samuels Syndicate                                    | 1898           | 302                | Dry  |
| 11... | Veale's, or Samuels No. 7; Samuels Syndicate                                   | 1899           | 1,345              | Dry  |
| 12... | Taranaki No. 4, Taranaki Petrol. Co.   | 1907           | 1,678              | Dry  |
| 13... | Bonithan No. 1, Bonithan F.P.E. Co.  | 1908           | 3,005              | Show oil and gas   |
| 14... | Bonithan No. 2, Bonithan F.P.E. Co.  | 1907           | 2,505              |  |
| 15... | Omata Bore; New Plymouth Petrol. Co.   | 1907           | 1,060              | Show oil and gas   |
| 16... | Mos; Moa Petroleum Co.   | 1908           | 460                | Traces of oil  |
| 17... | Norfolk Road; Inglewood, O. Bor. & Pros. Co.                                   | 1908           | 2,500              | Traces of oil  |
| 18... | Vogeltown, or Bullock's, Taranaki Oil & Fr. Co. (Ltd.)                         | 1909           | 1,385              | Show oil and gas   |
| 19... | Roy's, or Taranaki No. 2, Taranaki Petrol. Co.                                 | 1910           | 3,030              | Prod., 9,696 bbls., 1910-12  |
| 20... | Taranaki No. 5, Taranaki Petrol. Co.   | 1912           | 2,644              | Prod., 10,000 bbls. to June, 1914  |
| 21... | "Birthday," or Taranaki No. 1; Taranaki Petrol. Co.                            | 1914           | 2,340              | Flowed oil   |
| 22... | Samuels No. 4, or Taranaki No. 3, Samuels Synd. (Sold to Taranaki Petrol. Co.) | 1914           | 2,015              | Prod., 5,382 bbls., 1910-13  |
| 23... | "The Rotary"; Taranaki Petrol. Co.   | 1914           | 2,250              | Prod., 570 bbls.   |
| 24... | Bell Block No. 1   | 1914           | 2,820              | Show oil and gas   |
| 25... | Bell Block No. 2   | 1914           | 2,855              | Show oil and gas   |
| 26... | "Phoenix"; Phoenix Oil Co.   | 1914           | 2,300              | Show oil   |
| 27... | "Hadley's," or Carrington Road Bore; New Zealand S.O. Co., Ltd.                | 1914           | 3,240              | Show oil and gas   |
| 28... | Petch's; British Petrol. Dev. Co.  | 1914           | 360                | Show gas   |
| 29... | United   | 1914           | 500                | Show of gas  |
| 30... | Huiroa   | 1914           | 4,921              | Show of gas  |
| 31... | "Blenheim"; Blenheim Oil Co., or Tar. O.L. & D. Co.                            | 1914           | 5,680              | Initial, 50 bbls.; Prod., 2,980 bbls.  |
| 32... | Tarata No. 1, Taranaki Oil Fields Ltd.   | 1926           | 5,010              | Several showings of gas  |
| 33... | Moturoa No. 1, Taranaki Oil Fields Ltd.  | 1926           | 4,360              | Good showings of oil, several points. Gas (CO <sub>2</sub> = 72%) at 1,555 ft.; 5,000,000 cu. ft. per 24 hours; rock pressure 623 lbs. per sq. in. |

\* Compiled with assistance of Clarke's and other reports of New Zealand Geological Survey and records accumulated locally.

#### 7. EAST COAST DISTRICT

*General statement.*—What is known as the East Coast district includes parts of the former provincial districts of Auckland and

TABLE V\*  
ANALYSES OF TARANAKI NATURAL GASES†

| Kind of Gas         | ‡No. 1 | No. 2  | No. 3  | No. 4  | No. 5  | No. 6  |
|---------------------|--------|--------|--------|--------|--------|--------|
| Methane.....        | 95.50  | 95.10  | 95.70  | 93.70  | 95.00  | 95.40  |
| Olefines.....       | 0.43   | 0.44   | 0.42   | 0.41   | 0.43   | 0.44   |
| Carbon dioxide..... | 0.54   | 1.25   | 0.52   | 0.82   | 0.50   | 0.26   |
| Oxygen.....         | 0.14   | 0.14   | 0.15   | 0.63   | 0.20   | 0.17   |
| Nitrogen.....       | 3.39   | 3.07   | 3.21   | 4.44   | 3.87   | 3.73   |
| Totals.....         | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

\* E. de C. Clarke, *op. cit.*, p. 46.

† Dominion Laboratory, analyst.

‡ Source of the natural gases, with notes thereon: No. 1, Petch farm, Huatuki-iti Stream, 4 miles south of New Plymouth; No. 2, northeast edge of Inglewood; No. 3, near Norfolk Road Railway Station, 3 miles south of Inglewood; No. 4, Maungamauhete Stream, 4 miles southeast of Inglewood; No. 5, Bishop farm, Mangone Stream, 6 miles northeast of Inglewood; No. 6, Mangone Stream, 6 miles east of Inglewood.

TABLE VI  
ANALYSES OF GAS FROM MOTUROA, NEW PLYMOUTH\*

| Kind of Gas                         | ‡No. 7 | No. 8  | No. 9  |
|-------------------------------------|--------|--------|--------|
| Methane.....                        | 24.40  | 22.70  | 20.6   |
| Ethane.....                         | 16.30  | 25.80  | 4.7    |
| Carbon dioxide.....                 | 49.20  | 43.70  | 72.0   |
| Oxygen.....                         | 1.30   | 1.30   | nil    |
| Nitrogen and other inert gases..... | 8.80   | 6.50   | 2.7    |
| Totals.....                         | 100.00 | 100.00 | 100.00 |

\* Dominion Laboratory, analyst.

‡ No. 7, Well No. 2, Taranaki Petroleum Co.; No. 8, Well No. 3, Taranaki Petroleum Co.; No. 9, Moturoa Well No. 1, Taranaki Oil Fields Ltd., depth, 1,555 ft.

TABLE VII  
ANALYSIS OF OIL FROM NEW PLYMOUTH

| Distillate                         | Distillation Temperature (Degrees C.) | Percentage |
|------------------------------------|---------------------------------------|------------|
| Gasoline.....                      | 80-150                                | 20.2       |
| Kerosene.....                      | 150-300                               | 42.0       |
| Gas oil.....                       | 300-350                               | 12.8       |
| Paraffine and lubricating oil..... | 350 upwards                           | 15.1       |
| Coke.....                          | .....                                 | 9.9        |
| Total.....                         | .....                                 | 100.00     |

\* Professor F. A. Eastbaugh, analyst.

Hawkes Bay and forms a belt about 50 miles wide and 300 miles long the entire length of North Island, though indications and suitable structures are most prominent in the north, in what are known as the Poverty Bay and East Cape areas. Aside from local intermontane valleys, the district is generally mountainous and the population scant. The formations range from Triassic to Recent, and structurally the district is very much disturbed.

The East Coast district has been frequently studied in the past by geologists, and a list of the more important writings that pertain to oil is given at the end of this paper.

*Surface indications.*—Abundant surface indications of oil and gas exist, of which the most important are definite oil seepages of good commercial quality at Waitangi Hill, near Whatatutu, on Totangi station near Ngatapa, and on Rotokautuku block near Ruatorea. A deposit of bitumen resembling ozokerite could formerly be seen in the last-mentioned locality. About a hundred seepages of natural gas in the form of "vents," mud volcanoes, or gas "springs" are distributed all the way from the Bay of Plenty to Hawke's Bay, and from Raukumera Mountains to the coast. More seepages occur in the Poverty Bay and East Cape districts than farther south.

Some seepages have been described by Morgan<sup>2</sup> in southern Hawke's Bay, but the sources and structural characteristics do not appear as favorable as in the Poverty Bay and East Cape areas. Numerous saline springs exist, and salt water accompanies many of the gas emanations. In addition, Te Puia and Morere Hot Springs in the East Cape and Poverty Bay areas are summer resorts where saline water is accompanied by "escapes" of natural gas.

In composition the natural gases of the northern part of the district tend strongly toward "wet" gases. In Poverty Bay district the methane content ranges from 55 to 86; ethane, from 0 to 23; and unsaturated hydrocarbons, from 0 to 6 per cent among thirty-five samples analyzed. The following (Table VIII) are some of the typical gases:

A number of prominent black petroliferous shales are known in

<sup>2</sup> Percy G. Morgan, *New Zealand Mines Department, Geol. Survey Branch* (8th Annual Report, N.S., 1915), Appendix C-2, pp. 131-35.

the Awanui, an upper series of the Cretaceous period, and range in thickness from a few feet to more than 100 feet. These have been proved by analysis to contain 2 to 6 gallons of oil per ton of shale.

*General geology.*—The principal strata range in age from Cretaceous to Recent, and a number of important unconformities exist, rendering the determination of subsurface structure difficult. The

TABLE VIII  
ANALYSES OF TYPICAL GASES FROM EAST COAST DISTRICT\*

| Kind of Gas                         | †No. 1 | No. 2  | No. 3  | No. 4  | No. 5  |
|-------------------------------------|--------|--------|--------|--------|--------|
| Methane.....                        | 92.9   | 74.02  | 79.73  | 82.00  | 54.85  |
| Ethane.....                         | 1.7    | 21.69  | 9.79   | nil    | 14.65  |
| Unsaturated hydrocarbons.....       |        |        | 1.01   | 1.25   | 6.10   |
| Carbon dioxide.....                 | 0.7    | 0.75   | 1.26   | 3.75   | 3.20   |
| Oxygen.....                         |        |        | 1.64   | 2.60   | 2.45   |
| Nitrogen and other inert gases..... | 4.7    | 3.54   | 6.57   | 10.40  | 18.75  |
| Totals.....                         | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

\* Dominion Laboratory, analyst.

† No. 1, 1 mile, 40 chains southwest of Maori Creek, Oweha Stream junction, Matakaoa Survey district (J. S. MacLaurin, *57th Annual Report, Dominion Laboratory* [1925], p. 34).

No. 2, Tangakaka Block, Block XVI, Matakaoa Survey district (M. Ongley and E. O. Macpherson, *New Zealand Mines Department, Geol. Survey Branch, C-2c, 17th Annual Report, N.S.*, 1923, p. 5).

No. 3, Wickstead land, middle of north side of Hikurangi Survey district (J. S. MacLaurin, *55th Annual Report, Dominion Laboratory* [1919], p. 47).

No. 5, Totangi "bore" hole, Waikohu Survey district, Cook County (J. S. MacLaurin, *52nd Annual Report, Dominion Laboratory* [1919], p. 47).

thickness of the geologic section of the East Coast is great, and the figures given in the following table (Table IX) are not exaggerated.

Major unconformities are known at the close of deposition of the Tapuwaeroa, Taitai, Mangatu, Tutamoe, and Ormond (with Tokomaru) series and are designated the "Intra-Cretaceous," "Cretaceous-Tertiary," "Miocene-Pliocene," and "Post-Pliocene" unconformities. The relations of the intra-Cretaceous unconformity are in doubt and have relegated the Taitai beds to an extremely irregular distribution. The Taitai is in itself rendered of doubtful age by C. W. Washburne's impression that it may be an over-thrust of more ancient strata from the Raukumara Mountains on the west. In addition to the principal unconformities, local ones exist, unimportant except as sometimes deceiving the field geologist into a belief that he is dealing with a major unconformity.

The backbone of the east half of North Island, comprising the

Rimutaka, Tararua, Ruahine, and Raukumara mountain ranges is of Triassic age in the south, but in the north it is considered as being

TABLE IX  
GEOLOGIC COLUMN ON EAST COAST

| Period                 | Series or Formation |                              | Maximum Thickness (Feet) | Description   |  |
|------------------------|---------------------|------------------------------|--------------------------|---|--|
| Recent and Pleistocene | Waipaoa, etc.       |                              | 0-350                    | Gravel, sand, silt, and tuff  |  |
|                        | Unconformity        |                              |                          |   |  |
| Pliocene               | Ormond (1,300 ft.)  |                              | 2,300-8,000              | Gray fossiliferous clays, fine-grained massive sandstones, sandy shales, and fossiliferous sandy limestone  |  |
|                        | Tokomaru (Tawhiti)* |                              |                          |   |  |
| Upper Miocene          | Unconformity        |                              |                          |   |  |
| ?                      | Te Anau             | Tutamoe                      | 2,000-5,000              | Alternating sandstone and clay, shale, and some conglomerate  |  |
| Lower Miocene          |                     | Ihungia                      | 4,000-5,000              | Generally blue clay-shale ("papa"); igneous pebble conglomerate at base   |  |
| Eocene (?)             | .....               |                              | 0-3,000†                 | Basalt  |  |
|                        | Unconformity        |                              |                          |   |  |
| Upper Cretaceous       | Awanui Series       | Mangatu (Senonian)           | 4,000-6,000              | "Chalky" limestone (Amuri); light gray calcareous shales, blue-gray shales, beds of massive glauconitic sandstone, and several thick beds of black bituminous shale |  |
|                        |                     | Unconformity                 |                          |   |  |
|                        |                     | Tapuwaeroa (?Turonian)       | 2,000                    | Blue-gray shales, etc.  |  |
| Unconformity           |                     |                              |                          |   |  |
| Lower Cretaceous       | Awanui Series       | Taitai‡                      | 2,000                    | Massive sandstone, hard conglomerate, and rarely glauconitic sandstone  |  |
|                        |                     | Raukumara (Albian and lower) | 7,000                    | Greywackes and argillites, with a mudstone in upper part  |  |
|                        |                     | Unconformity                 |                          |   |  |
| Jurassic               |                     | ?                            | ?                        |   |  |
| Triassic.....          | Manawatu            |                              | 10,000+                  | Hard, crushed, folded, metamorphic and veined slates, shales, and sandstone   |  |

\* Increases from less than 2,500 ft. north of Gisborne to perhaps 8,000 ft. in Hawkes Bay district. Since the name Tawhiti has been used elsewhere in New Zealand for other formations, its use is abandoned on East Coast.

† Absent in south; thick only near Hicks Bay, in extreme north.

‡ Position in doubt; may be an overthrust of older rocks, much folded.

mainly of Jurassic age. The Raukumara Mountains in the Poverty Bay area are bordered on the east by Cretaceous sediments, which reach the coast throughout a considerable area in the East Cape area and also outcrop at scattering points elsewhere. The major part of the area between the Raukumara Range and the sea is, however, composed of Miocene and Pliocene strata, the former occupying many of the uplifts, whereas the Pliocene strata occupy the great synclines.

*Source rocks, containers, and covers.*—Aside from the appreciably petroliferous shales, previously mentioned, thousands of feet of clays of marine origin exist that occasionally contain noticeable fossils and abound in *Foraminifera*. There is little doubt that suitable rocks exist from which oil may have been generated in quantity. Several porous sandstone beds of Cretaceous and Miocene ages ranging in thickness from a few feet to several hundred feet exist throughout the district. The texture is varied, having in places an extremely fine-grained character and in others being conglomeratic. The pore space in some typical sandstones has been determined experimentally and found to range from 5 to 32 per cent, with an average of 18 per cent pore space in six samples tested. The thousands of feet of impervious shale and clay, of both Cretaceous and Tertiary ages, would act as an ideal cover to prevent the escape of any oil that may exist in interlaminated "sands."

*Structure.*—Geologic structures of the East Coast are similar in certain respects to some of the tightly closed California and Colombia anticlines, and in other respects to the *diapir* anticlines of Rumania and Italy. Poverty Bay area forms part of a great sedimentary district situated between the Pacific Ocean and the mountain ranges, in which the strata have been folded or tilted into sharp anticlines and broad synclines, controlled by faulting. Although the oil deposits may lie deep, several structures are known in which oil is believed to lie within reach of drilling. The major axes trend most commonly northeast and southwest, but in the East Cape area, and to some extent in Cretaceous beds in the vicinity of Poverty Bay, the trend is northwest and southeast. The areas of uplift are not regular from one end of the district to the other, but extend a few miles, die out, and frequently overlap, and are such that any

section from the Raukumaras to the sea will cross several structural axes.

Controversy has been waged among New Zealand geologists as to whether the structures are true folds or whether they are due to tilting influenced entirely by faulting. Studies made in the Poverty Bay region by the writer and his assistants, P. B. Whitney and W. D. Miller, on behalf of Taranaki Oil Fields Ltd. indicate that both faulting and folding have operated extensively. The crests of some of the prominent folds have been intensively crushed in zones ranging in width from a few hundred feet to half a mile, in which the underlying plastic Cretaceous or Ihungia clays have flowed upward in a manner perhaps analogous to the action of salt in the "diapir" structures of Rumania and Texas, and like shale in those of Italy. Credit is due C. W. Washburne for first suggesting the "diapir" analogy in a company report.

The principal fractures of the Poverty Bay district maintain, roughly, a northeast-southwest trend. A nearly constant association of mineral springs, sinter deposits, gas emanations, mud volcanoes, and oil seepages with the faults and crushed zones proves that fractures control the distribution of these phenomena. Surface slips and slumps, although occurring in almost any situation, are exceedingly prevalent in the crushed zones. For this reason the belts of "pug," or plastic clay, are characterized by a topography more subdued than that of the bordering unshattered strata. In such structures the dips increase from gentle on the flanks to  $70^{\circ}$  in places adjoining the central crushed zone.

Other structures have a milder form in which no trace of central crushing has been discovered and where the maximum dips are not over  $30^{\circ}$ , so that anticlines and faulted domes of many types exist. In all, about 30 structural areas were mapped in preliminary work as worthy of detailed investigation, and at least six have been "detailed" by Messrs. P. B. Whitney and W. D. Miller, assisted by E. H. Hunt, O. H. Penny, and others. Credit is due E. O. Macpherson for discovery of some of the structures, and others were reported by the government.<sup>1</sup>

*Metamorphism.*—In considering the effect of metamorphism on

<sup>1</sup> J. H. Adams, *Bulletin* 9, and J. Henderson and M. Ongley, *Bulletin* 21.

rocks of the different ages, no evidence was found in the north (except possibly in the very oldest or Raukumara series) of metamorphism severe enough to distil away oil that once existed. The Tertiary strata are unconsolidated clays and sands and obviously unmetamorphosed. In the Mangatu and Tapuwaeroa series of Cretaceous age there is little evidence, but such evidence as is apparent does not preclude the occurrence of oil from the standpoint of metamorphism.

Some light was shed on metamorphism, for the writer has actual information of carbon ratios. He is informed by Mr. P. G. Morgan, government geologist, that Messrs. Ongley and Macpherson, of the New Zealand Geological Survey, found a few thin coals in probably Cretaceous rocks in Waiapu County in the northern part of the East Coast area, and these, when analyzed and subjected to the carbon ratio determination, give figures well within the safety limit. In addition, a sample of coal collected on the property of Mr. G. Richardson within half a mile of Motuhora, near Motu (evidently washed down from higher up the valley), and therefore presumably of Cretaceous or Jurassic age, was analyzed for Mr. A. H. Kimbell, under-secretary of mines, with the following result:

## ANALYSIS OF COAL FROM MOTUHORA\*

| Substance                  | Percentage |
|----------------------------|------------|
| Fixed carbon.....          | 59.73      |
| Volatile hydrocarbons..... | 39.01      |
| Water lost at 100.....     | 0.76       |
| Ash.....                   | 0.50       |
| Total.....                 | 100.00     |
| Sulphur.....               | 0.33       |

\* Dominion Laboratory, analyst.

Computation from these figures gives a carbon ratio of 60.7, which indicates that metamorphism in some of the Cretaceous or Jurassic areas is not too great to permit the presence of oil.

*Tectonic aspects and paleogeography.*—A study of tectonic and paleogeographic evidences in the islands extending from New Zealand northwest to Netherlands East Indies, reveals the existence of a zone in which certain fundamental conditions are similar to those of New Zealand and potentially favorable to oil occurrence. Geologists have

remarked on this coincidence of features and have delineated "arcs" or "festoons" to explain the trends.<sup>1</sup> Fossil forms in strata of identical age are correspondingly similar; rocks are similar lithologically; and the faulting and intense earth movements conspicuous in eastern New Zealand have taken place on a similarly large scale on other islands in the belt. The oil seepages of New Zealand and New Guinea appear to fall within the same tectonic belt as do the fields of the East Indian archipelago.

A study of fault conditions seems to controvert frequent assertions that New Zealand is "too much broken up" to hold oil. Notwithstanding the fact that the district is cut by immense faults and crushed zones, these are not considered unfavorable. The argument that all of the oil may have leaked away in the past is disproved, since the most important seepages lie on some of the most pronounced faults and crushed zones; whereas, if oil had largely disappeared in the past, any remaining seepages would lie on the *least* broken uplifts. The fact that the seepages are situated on pronounced "breaks" is evidence that such fractures provide the only adequate means of escape, hence oil doubtless still remains under some structures from which an easy escape does not exist. Earthquakes are prevalent, and seismic and volcanic phenomena may have some bearing on the subject, but only from the standpoint of assisting in explaining the genesis of the structures. Only a few small outcrops of a vesicular basaltic rock a few rods in diameter are known in the East Coast district, except near Cape Runaway and Hicks Bay in the extreme north, and are not sufficient to affect the occurrence of oil over any considerable area.

*Outline of past drilling.*—Several attempts were made to find oil in the East Coast between 1874 and 1919. Holes were drilled near the oil seepages at Waitangi Hill near Whatatutu in Waikohu County, 23 miles north-northwest of the center of Gisborne; on and near Rotokautuku block, about 3 miles northwest of Ruatorea in Waiapu County; on Totangi sheep "station," or Tangihanga block, in Cook County 15 miles northwest of Gisborne; at Waihirere in Cook County, 8 miles northwest of Gisborne; at Waipatiki, 20 miles

<sup>1</sup> Edward Suess, *The Face of the Earth*, Vol. 4 (1909), p. 301; J. W. Gregory, *Geography; Structural, Physical, and Comparative* (1908), p. 275.

east of Woodville; and at a point 4 miles east of Eketahuna, in Hawke's Bay district. Good showings of oil were found in one of the Waitangi wells, at Rotokautuku, and at Totangi, and showings of gas were found at Waihirere and reported in the easternmost Waitangi test well on Waingaromia River. Neither oil nor gas has yet been encountered in proved commercial quantity.

An outline of all wells known to have been drilled in the East Coast district (Table X) will be of interest.

TABLE X  
WELLS DRILLED IN EAST COAST DISTRICT

| No.  | Locality             | Company                          | Date    | Total Depth | Result               |
|------|----------------------|----------------------------------|---------|-------------|----------------------|
| 1..  | Waitangi Hill        | Poverty Bay Oil Co.              | 1874-75 | 210         | Oil                  |
| 2..  | Waitangi Hill        | South Pacific Oil Co. Wells 1-8  | 1882-86 | 400-470     | Shows of oil         |
| 3..  | Waingaromia Valley   | South Pacific Oil Co. No. 9      | 1887    | 1,321       | Gas (?)              |
| 4..  | Waipaoa Valley       | Minerva Petrol. Co.              | 1887-88 | 750         | Dry                  |
| 5..  | Waitangi Hill, No. 1 | Gisborne Oil Co.                 | 1909    | 1,478       | Oil                  |
| 6..  | Waitangi Hill, No. 2 | W. D. Lysner and John Clark      | 1919    | 845         | Dry                  |
| 7..  | Ruatorea             | Southern Cross Petrol. Co. No. 1 |         | 400+        | Show of oil          |
| 8..  | Ruatorea             | Southern Cross Petrol. Co. No. 2 | 1881-83 | 500+        | Dry                  |
| 9..  | Ruatorea             | Southern Cross Petrol. Co. No. 3 |         | 400+        | Dry                  |
| 10.. | Ruatorea             | Southern Cross Petrol. Co. No. 4 |         | 100+        | Dry                  |
| 11.. | Ruatorea             | Southern Cross Petrol. Co. No. 5 | 1883    | 1,836       | Gas                  |
| 12.. | Totangi Station      | London Oil Syndicate No. 1       | 1897    | 338         | Trace of oil and gas |
| 13.. | Totangi Station      | London Oil Syndicate No. 2       | 1897    | 258         | Show of gas          |
| 14.. | Totangi Station      | N.Z. Oil Fields Ltd. No. 1       | .....   | 273         | Dry                  |
| 15.. | Totangi Station      | N.Z. Oil Fields Ltd. No. 2       | .....   | 513         | Dry                  |
| 16.. | Waihirere            | N.Z. Oil Fields Ltd.             | 1912    | 1,381       | Show of gas          |
| 17.. | Waipatiki No. 1      | "Shell" Co.                      | .....   | 1,800       | Dry                  |
| 18.. | Waipatiki No. 2      | "Shell" Co.                      | .....   | 3,600       | Show of oil and gas  |
| 19.. | Eketahuna No. 1      | "Shell" Co.                      | .....   | 3,000       | Trace of oil and gas |
| 20.. | Ruatorea             | Taranaki Oil Fields Ltd.         | 1926    | 2,540       | .....                |

*Drilling in vicinity of Waitangi Hill.*—The test wells drilled on and near Waitangi Hill<sup>1</sup> may be classified as (a) old shallow prospect holes (5-210 ft.), (b) Gisborne Oil Company's "bore" or Waitangi No. 1 (1,478 ft.), (c) South Pacific "bores" Nos. 1-9 (400-1,321 ft.), (d) Minerva "bore" (750 ft.), and (e) the Lysnar-Clark "bore," or Waitangi No. 2 (845 ft.). These borings were all made within 5 miles east and northeast or 1 mile northwest of Whatatutu.

The first of these attempts to develop oil at Waitangi appears to have been in 1874-75, made by a syndicate from Taranaki, on the basis of which Poverty Bay Oil Company was organized. In 1875 a timbered shaft was sunk 100 feet deep, which still was visible until a

<sup>1</sup> P. G. Morgan, *New Zealand Mines Department, Geol. Survey Branch, C-2* (8th Annual Report, N.S., 2d ed., 1915), p. 126.

few years ago. In the bottom of the shaft an additional 110 feet were drilled. The *Poverty Bay Herald* of November 26, 1874, is authority for the statement that "8-10 gallons of oil per day were obtained from a depth of 17 feet." It is said the workmen were overcome by natural gas. Other shallow pits were dug at about the same time.

The next attempt seems to have been in 1882, when the South Pacific Petroleum Company took over the plant and sank three or four holes 400 or 500 feet deep. The plant was then moved a short distance and a hole drilled 600 feet. Traces of oil were found, but salt water was encountered below 470 feet. A "trial bore" 2 inches in diameter and 200 feet deep was also sunk, from which oil flowed over the casing "for several months." A new outfit was procured and more holes were sunk, but none of them reached any considerable depth.

After drilling these shallow holes without great success the company moved into Waingaromia Valley, 2 miles south of the main oil seepage. The hole reached a depth of 1,321 feet in December, 1887, when a "blow-out" is alleged to have taken place; "the gas and oil became ignited, the derrick was burnt to the ground, and much of the equipment destroyed." Nearly every person describing this blow-out has referred to the possibility that it was fictitious, and some have maintained that it was "salted" with kerosene, but one authority<sup>1</sup> states that when he and Mr. R. J. Walker visited the locality soon after the event they actually drew oil "that was *not* kerosene" out of the well.

The site for a decisive test was then selected by the New Zealand Geological Survey and a hole ("Waitangi No. 1") was started by the Gisborne Oil Company in 1909 and drilled to a depth of 1,478 feet. Mr. M. P. Poole, a former resident of Whatatutu, states that at least 8 or 10 barrels of oil were produced and that the capacity was about 2 barrels a day from a depth of 655 feet. The casing still stands, and a little gas constantly bubbles through the fresh water that fills it. Perhaps a gallon of oil, brown by transmitted, and dark green by reflected, light, which will burn if ignited, now floats on the water that has overflowed and accumulated in a hollow. For

<sup>1</sup> Henry Hill, *Transactions of the New Zealand Institute*, Vol. 39 (1906), p. 510.

structural determinations five shallow bores within a radius of 1,400 feet from the site of this well were sunk to a depth of 60 feet by the Gisborne Oil Company. The results are appended (Table XI) of an analysis of oil from 845 to 859 feet below the surface in this well, made at the request of the writer.

In 1887-88 the Minerva Petroleum Company drilled a hole 750 feet deep just east of Waipaoa River, 5 miles west-southwest of the

TABLE XI  
RECENT ANALYSIS OF WAITANGI OIL\*

| Distillate                              | Distillation Temperature (Degrees C.) | Percentage | Sp. Gr. at 15.5°C. |
|---|---------------------------------------|------------|--------------------|
| Gasolene.....                           | Below 150°                            | 21.3       | 0.740              |
| Kerosene.....                           | 150° to 300°                          | 34.2       | 0.819              |
| Gas oil.....                            | 300° to 350°                          | 15.5       | 0.856              |
| Lubricating oil.....                    | 350° upwards                          | 22.2       | 0.871              |
| Coke and loss.....                      |                                       | 6.8        |                    |
| Total.....                              |                                       | 100.0      |                    |
| Paraffin (melting point, 46.5° C.)..... |                                       | 3          |                    |

\* Dominion Laboratory, analyst.

main oil spring and one mile northwest of Whatatutu. Morgan reports that a small quantity of "white oil" was found, some gas was encountered at 700 feet, and at the bottom a brown shale impregnated with oil was entered.

During 1919 W. D. Lysner and John Clark, of Gisborne, drilled Waitangi No. 2 on Waitangi Hill half a mile east-southeast of Waitangi No. 1 well. The depth was 845 feet. Only a small showing of oil was found in a fault plane.

*Drilling in vicinity of Ruatorea.*—In 1881 the Southern Cross Petroleum Company commenced drilling on Rotokautuku block, west and northwest of Ruatorea, Waiapu County, between Mangaporo and Tapuwaeroa streams, close to a long-known bituminous dike and seepage. Five holes, ranging in depth from 150 feet to 1,820 feet, are reported<sup>1</sup> to have yielded more or less gas, and No. 1 had notable showings of oil.

The first test, 1½ miles northwest of Ruatorea, began as a circular,

<sup>1</sup> Morgan, *op. cit.*

boarded shaft 200 feet deep and 6 feet in diameter, strengthened with angle irons. In the bottom of this shaft a hole was drilled to a total depth of 400 or 500 feet from the surface. Considerable gas and at least 4 barrels of oil were obtained. This hole is situated in the center of an acre or more of black soil which still shows signs of having been on fire and is reported to have once burned continuously "for a year or two." The abandoned shaft later filled with salty water, through which bubbles of gas still rise rapidly and yield films that accumulate as light-brown oil.

No. 2 hole of the same company appears to have been drilled one mile northeast of No. 1 and reached a depth of 500 or 600 feet, "entirely in river deposits of gravel, sand, and clay." The third test was near a gas vent about a mile west of No. 1, and attained a depth of only 400 to 500 feet. The fourth hole was drilled close to No. 1 and never reached below the bottom of the shaft of Number 5, completed in 1883, was located  $1\frac{1}{2}$  miles up Tapuwaeroa Valley, above No. 3 and half a mile distant from a gas vent. Its total depth is reported 1,836 feet. Gas encountered in the hole was used for fuel, and showings of oil were reported.

*Drilling on Totangi "station."*—Four shallow holes were drilled at different times on Totangi sheep station, Tangihanga block, Cook County, 6 miles northwest of Ormond or 15 miles northwest of Gisborne, air-line distances. The first attempt, about 1897, made by the London Oil Syndicate, was 338 feet deep near an old oil spring on a hillside. Mr. T. Smith, driller, states in a personal letter that he got a little oil at 285 feet and traces of naphtha and gas at 310 feet. A little gas is said to have been encountered at 55, 140, and 180 feet from the surface. In 1907 bubbles of gas were rising through the pipe;<sup>2</sup> a trace of oil is still evident on fresh water surrounding it, and gas is said to be often manifest. The second hole was sunk in the valley three-fourths mile south-southeast of No. 1, and the same driller reports "plenty of gas" at 258 feet and "slight traces of oil."

At a later date the New Zealand Oil Fields Ltd. drilled on Totangi station, a few feet from the London Oil Syndicate's No. 1, to a depth of 273 feet, 65 feet less than that of the original hole on the

<sup>2</sup> Frank A. Rich, *Report on the East Coast Petroleum Fields* (Auckland, 1907), 10 pages, 1 plate.

same site. A well 14 inches in diameter was then commenced about 700 feet north, but was abandoned at 513 feet.

*Drilling at Waihirere.*—The Waihirere test well was sunk on a mud hill  $1\frac{1}{2}$  miles southwest of Ormond, a mile northeast of Waihirere railway station, Cook County, and 5 miles north of Gisborne, a few hundred feet east of prominent gas springs. This hole was drilled by the New Zealand Oil Fields Ltd. to a depth of 1,381 feet; considerable gas and traces of oil were reported,<sup>1</sup> and gas still rises occasionally through water which fills the 10-inch pipe.

*Present operations.*—In 1925 the Gisborne Oil Proprietary Ltd. entered the East Coast district, conducted extensive geologic work, leased up a large acreage covering the most favorable structures, and made all preparations for drilling several test wells. A hole was drilled 2,540 feet deep on a location near Ruatorea. The properties of the company have since been acquired by Taranaki Oil Fields Ltd. Other wells are about to be commenced.

*Petroliferous shales of Poverty Bay and East Cape districts.*—Outcrops of dark brown to black shales from which petroleum can be distilled exist in the Mangatu series at many localities in Poverty Bay and East Cape districts, and they extend under the entire northern areas between the Raukumara range and the coast. The best-known exposures are 100 feet thick. At least three similar shale beds are known in the north, some being as much as 20 feet thick. The shales are soft, black, somewhat earthy, have a conchoidal fracture, cut like wax, and yield both liquid and gaseous hydrocarbons on distillation. Samples collected by the writer without regard to their apparent content gave the following results (Table XII):

The specimens were small hand samples, and as a check on the accuracy of the analyses, a 5- or 10-pound sample was later collected for the writer from the second-mentioned locality and distilled, with the results that 2.35 gallons per ton of oil were obtained.

*East Coast summary.*—The East Coast district of New Zealand has nothing in common with the Taranaki field, and experience gained in Taranaki should not be used as a guide as regards geology or technology of the East Coast. Taranaki has persistent dips of

<sup>1</sup> P. G. Morgan, *op. cit.*, p. 127.

very low angle, whereas the East Coast structures are sharp, interruptions in strike and dip are many, and faults are common. The Cretaceous beds, which form a prominent part of the East Coast section, do not exist in Taranaki. The East Coast has few igneous intrusions, and has no wide dairy plains like those in western Taranaki.

Owing to complicated structural conditions and thick rock sections, the difficulties in drilling will be many; therefore the very

TABLE XII  
ANALYSES OF BITUMINOUS SHALES\*

| Substance                                     | †No. 1 | No. 2  |
|---|--------|--------|
| Fixed carbon.....                             | 4.88   | 3.29   |
| Volatile hydrocarbons, etc.....               | 9.74   | 8.33   |
| Water lost at 100° C.....                     | 2.56   | 3.42   |
| Ash.....                                      | 82.82  | 84.96  |
| Totals (percentage).....                      | 100.00 | 100.00 |
| Gallons of oil per ton (2,240 lbs.) of shale. | 6.1    | 2.0    |

\* Dominion Laboratory, analyst.

† No. 1, Mangatu Road, 1½ miles north of Iwi-roa P.O., Waikohu County;  
No. 2, Outcrops in front of hotel, Port Awanui, Waikohu County.

best equipment should be used in prospecting. An outfit should be ordered only after consideration of all local requirements by an experienced drilling superintendent, comprising inspection of the field and a study of its drilling problem in consultation with geologists familiar with the local details. A "combination" outfit with core-barrel attachment may be expected to prove most suitable, and superintendents should be experienced in both "standard" and "rotary" methods and with fields offering a wide diversity of problems.

#### CONCLUSION

In concluding this digest of New Zealand oil prospects, the writer takes pleasure in acknowledging the permission of Taranaki Oil Fields Ltd. to make the information public. Especially is his appreciation due for many courtesies extended by official representatives of the company, Right Hon. W. A. Watt, chairman; Colin

Fraser, managing director; E. H. Shackell, secretary; A. H. P. Moline, general manager; and Chas. N. Taylor, assistant general manager; and by Thomas Baker, chairman of Gisborne Oil Proprietary Ltd. The company's attorneys—Messrs. Nolan and R. F. Gambrill, of the firm of Nolan and Skeet, of Gisborne—have been of valuable assistance. Samples of oil from Waitangi well No. 1 were furnished by them and by Mr. M. P. Poole, of Gisborne. It is likewise a pleasure to mention the helpfulness of Mr. Albert Edward Broué, of Sydney, through whose vision the Australasian explorations were initiated and whose enthusiasm has been a dominant factor in acquiring data in both East Coast and Taranaki districts. The various geologists employed by Taranaki Oil Fields Ltd. have been referred to herein, and in addition Mr. Percy G. Morgan, government geologist, and his assistants have been helpful. Mr. A. W. Donald, of Auckland, originally interested in the Taranaki venture, has been helpful in many ways. Mr. A. H. Kimball, under-secretary of mines, and members of his department have been enthusiastic advisers throughout; the government analyst, Mr. J. G. Maclaurin, has made valuable analyses and porosity tests; while Mr. J. A. Bartrum, of University College, Auckland, has made lithologic determinations. Other persons have supplied well logs and data on seepages.

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## MECHANICS OF THE BALCONES AND MEXIA FAULTING

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### ABSTRACT

The Balcones and Mexia fault zones are groups of tension fractures curving about the eastern and southern sides of the Llano uplift. This paper describes experiments which show that the subsidence of the coastal plain region, resisted by the support of the Llano positive element, would cause tension fractures curving about the eastern and southern sides of the Llano uplift. A bibliography accompanies the paper.

The Balcones and Mexia fault zones occur in eastern and south-eastern Texas. The Balcones fault zone extends southwestward from Rockwall County to Bexar County, and thence in a more westerly direction across Medina and Uvalde counties. The Mexia fault zone extends from Kaufman County southwestward across Navarro and Limestone counties and is reported to extend across Falls, Milam, Bastrop, and Caldwell counties. The distribution of these faults is shown in Figure 1. These faults have been studied in great detail because of their relation to oil accumulation. Because of the economic significance of this information, very little of it is available for publication and the maps are necessarily generalized and very incomplete.

The faults of both fault zones are of the normal, or gravity, type. The total displacement of the Balcones fault zone is about 1,000 feet, and the average displacement of the Mexia zone is about 400 feet. The downthrow of the Balcones fault zone is to the southeast, but that of the Mexia zone is to the northwest, forming a *Graben* between the two fault zones which is more than 30 miles wide. This *Graben* itself is highly faulted.

The faulted rocks at the surface are of Cretaceous age in the Balcones zone, and of Eocene age in the Mexia zone. Baker<sup>1</sup> has

<sup>1</sup> C. L. Baker, "Review of the Geology of Texas," *University of Texas Bulletin* 44 (1919), p. 122.

correlated the latest movement along the Balcones zone with the late Pliocene folding in southwest Texas.

The relation of the fault zones to the other structural features of this region is shown in Figure 2. The regional structure of the Cretaceous beds is a southeastward-dipping monocline. The average

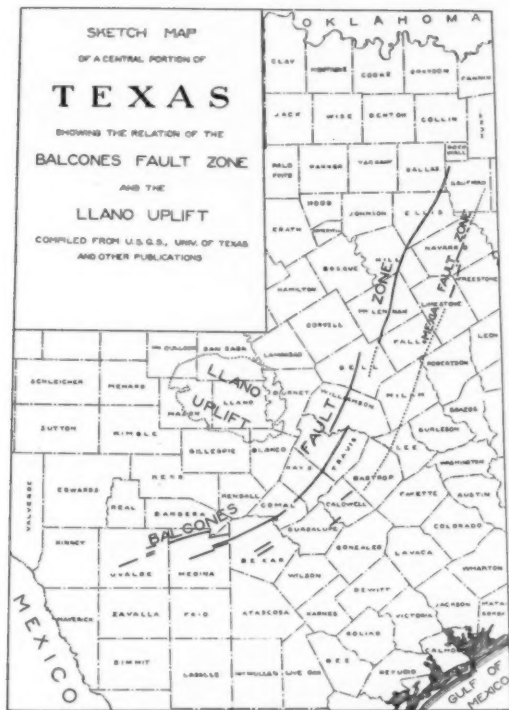


FIG. 1

rate of dip is about 10 feet a mile in the region to the west of the Llano uplift, and about 40 feet a mile in the coastal plain region. This monoclinal dip is modified by the East Texas embayment, which is a broad shallow syncline lying between the Llano and Ouachita uplifts, and by the Rio Grande embayment which lies

south of the Llano uplift. Between these two embayments is a broad low arch extending southeastward from the Llano uplift.

The result of the Balcones and Mexia faulting has been a lengthening of this portion of the earth's crust, and therefore these faults may be considered to have been caused by tensional stresses.

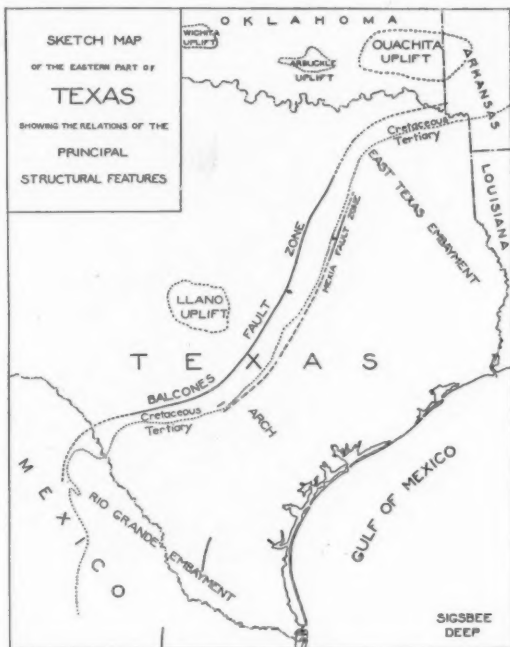


FIG. 2

The fault zones are, essentially, curved groups of tension fractures and their symmetrical arrangement with respect to the Llano uplift is very striking.

The fault zones are very nearly parallel to the strike of the formations, and it is noteworthy that similar faults to the south in Mexico are parallel to the regional strike.

Hill<sup>1</sup> considered that the Balcones fault zone was "probably due

<sup>1</sup> R. T. Hill, "Geology and Geography of the Black and Grand Prairies," *U. S. Geol. Survey, Twenty-first Ann. Rept., Part 7* (1900), p. 385.

to the adjustment by weight of the Cretaceous rocks to the slope of the buried eastern margin of the Wichita peneplain." Other writers have suggested that these faults were due to readjustments of the earth's crust caused by a sinking of the Gulf coastal region under the heavy load of Cretaceous and Tertiary sediments.

A series of experiments was performed by the writer at the suggestion of Dr. F. H. Lahee to determine what kinds of stresses might

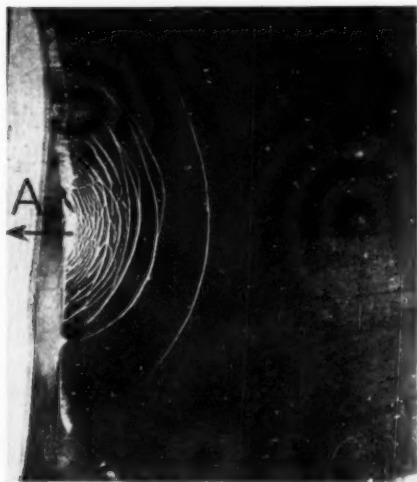


FIG. 3.—Fractures developed by linear tensional stress, *A*, in paraffin coating on rubber sheet.

cause fractures of the type of these fault zones. Paraffin-coated rubber sheets similar to those used by Mead<sup>1</sup> were used in these experiments.

It was found that a linear tensional stress applied to a side of the sheet would cause tension fractures curving about the point of application of the stress, as shown in Figure 3. The relation of the fractures to the point of application of the stress is very similar to the relation of the Balcones and Mexia fault zones to the Llano uplift.

<sup>1</sup>W. J. Mead, "Notes on the Mechanics of Geologic Structure," *Jour. of Geol.*, Vol. 28 (1920), p. 505.

An analysis of the stresses involved in this experiment is shown in Figure 4a. The linear tensional stress,  $A$ , is resolved into components,  $R$ , radiating about the point of application of the stress. The resistance of the material to deformation sets up resisting stresses,  $R_i$ , which oppose the resultant forces,  $R$ . Figure 4b shows how radiating tensional stresses may produce a linear resultant resisting stress.

The application of these principles to the Balcones and Mexia fault problem is shown by the experiment illustrated in Figure 5. The apparatus for this experiment consisted of a paraffin-coated rubber sheet stretched on a hollow wooden frame. This frame was hinged on the axis  $AB$ , a support was placed under the rubber sheet at  $C$ , and the frame was warped downward about the axis  $AB$ . This downward warping caused tension stresses in directions radiating outward from the point of support, and caused the formation of groups of tension fractures curving about the point of support.

This experiment simulates the downward warping of the Cretaceous and Tertiary sediments over the supporting Llano positive element and shows how this downward warping might set up tensional stresses in directions radiating from the Llano uplift. Such tensional stresses would cause faulting of the Balcones and Mexia type.

It is obvious that such faults, due to downward warping and curving outward around uplifts as here shown, would curve inward around synclinal embayments. This is illustrated by the faults in Mexico and southern Texas. It is to be expected, therefore, that the Balcones and Mexia fault zones, if continuous to the north, would swing eastward around the East Texas embayment and pass south of the Ouachita uplift.

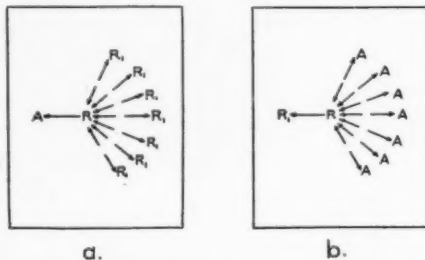


FIG. 4.—An analysis of the stresses involved in the experiment shown in Figure 3.  $A$  is the active force;  $R$  is the resultant force;  $R_i$  is the resisting force.

The planes of simple tension fractures are normal to the direction of tension. The fractures formed in these experiments followed this rule, and since the tension was applied horizontally, the dips of the

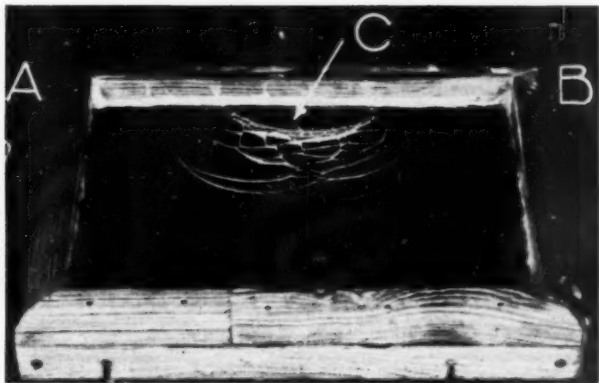


FIG. 5.—Fractures developed in paraffin coating on a rubber sheet stretched on a hollow wooden frame. The frame was hinged on the axis *AB*, a support was placed under the rubber sheet at *C*, and the edge nearest the reader was warped downward.

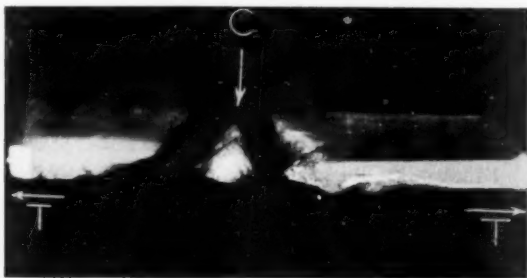


FIG. 6.—A cake of paraffin wax showing fractures developed by combined vertical compression and lateral tension. *C* is vertical compression, *T* is lateral tension.

fractures were vertical. The fracture planes of the fault zones dip at angles of about  $45^\circ$ , due to the modification of the conditions of simple tension by the weight of overlying sediments which have since been removed by erosion. The effect of combined vertical compres-

sion and lateral tension is shown by the experiment illustrated in Figure 6, which shows a cake of paraffin wax which has been subjected at the same time to vertical compression and lateral tension. Instead of vertical fractures due to simple tension, inclined shear fractures were formed. This principle has long been recognized by engineers in their work on beams and floors. The tension stresses due to the flexure of beams will modify the conditions of vertical shear due to the load, and the fractures due to combined tension and shear will form diagonally. These fractures in simple beams dip toward the supports, but those in cantilever and in overhanging continuous beams dip away from the supports, as illustrated in Figure 7. It is interesting to note that in cantilever beams of considerable thickness the shear fractures have been observed to steepen in dip toward the lower part of the beam.

Many writers have noted that normal faults are commonly inclined instead of vertical. The usual explanation of this has been that the yielding due to tension has taken place along pre-existing fractures. It is evident, however, that the inclined fractures are not necessarily pre-existing, but may be formed during the application of the tension. At the time of deformation, the Cretaceous rocks were supported firmly by the Llano positive element and were free to move downward in the eastern part of the section. The stress and strain relations were therefore approximately those of a cantilever, or possibly of an overhanging continuous beam or floor. The fractures would be expected to dip away from the support, or to the southeast, as is the case in the Balcones fault zone. The faults of the Mexia zone are possibly due to readjustment incidental to the Balcones faulting, and consequently dip toward the Balcones zone.

The conclusions drawn from these experiments are here stated: The Balcones and Mexia faulting was due to tensional stresses caused by subsidence in the Gulf coastal region. These stresses were modi-

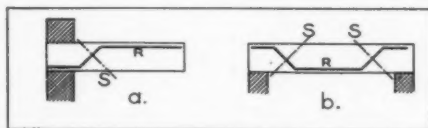


FIG. 7.—Showing how shear fractures form in (a) cantilever beams, and (b) in simple beams. *S* indicates the lines of modified shear. *R* indicates the reinforcement of the beam against shear and tension.

fied by the support of the Llano positive element, causing the fault zones to curve around the southeastern side of the Llano uplift. The Balcones and Mexia fault zones, if continuous to the north, may be expected to swing east and pass south of the Ouachita uplift.

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## THE PROBLEM OF THE NATURAL REDUCTION OF SULPHATES

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AND GAIL MOULTON

### ABSTRACT

The reduction of sulphates in natural waters through the agency of sulphate-reducing bacteria with the generation of hydrogen sulphide has been thoroughly established by the work of many observers dating back to 1886. The situations in which such bacteria have been found include river muds, brackish canal muds, sewerage, soils, lake sands, dune sands at depths to 37 meters, black muds of the ocean bottom to depths of 16 fathoms, and bottom muds of the Black Sea to depths of 2,118 meters. Three species of sulphate-reducing bacteria have been isolated and described.

Many of the waters associated with petroleum in oil pools are so low in sulphates as to indicate that a natural reduction of sulphates has been in progress. This fact has been recognized by several observers but the reduction was attributed by them to the petroleum, that is, to dead organic matter. Available experimental data fail to afford any evidence that dead organic matter is capable of reducing sulphates at ordinary temperatures although such reduction can proceed at high temperatures.

With the usual precautions observed in bacteriological work, water samples were collected from thirty producing oil wells of Illinois ranging in depth from 400 to 1,866 feet and producing from Ordovician, Mississippian, and Pennsylvanian horizons. These waters were low in sulphate, and all but two carried sulphate-reducing bacteria. The active bacterium was isolated from pure cultures and photographed.

The study was extended to the Sunset-Midway and Coalinga oil fields of California, and a sulphate-reducing bacterium was found to be abundant there in many of the low sulphate waters of oil wells producing from depths ranging from 760 to 3,090 feet. The productive horizons are Miocene and Pliocene. Waters of the eastern and deeper part of the Sunset-Midway field though low in sulphates do not at present carry sulphate-reducing bacteria although they may previously have done so. The temperatures of many of the California waters are higher than for the Illinois waters, 40°-47° C. being not uncommon. The sulphate-reducing bacterium of the California wells functions similarly in general to that in the Illinois waters but appears to be tolerant of higher temperatures. It has not yet been isolated from pure cultures.

### STATEMENT OF THE PROBLEM

The reduction of sulphates in sea water and the waters of springs through the agency of living microscopic organisms has been well established by the researches of many observers. The following

equations are types of those which have been postulated by these observers to explain the results of such reactions of metabolism.

- 1a.  $\text{CaSO}_4 + \text{CH}_4 = \text{CaS} + \text{CO}_2 + 2\text{H}_2\text{O}$
- 1b.  $\text{CaS} + \text{CO}_2 + \text{H}_2\text{O} = \text{CaCO}_3 + \text{H}_2\text{S}$
- 2a.  $\text{Na}_2\text{SO}_4 + \text{CH}_4 = \text{Na}_2\text{S} + \text{CO}_2 + 2\text{H}_2\text{O}$
- 2b.  $\text{Na}_2\text{S} + \text{CO}_2 + \text{H}_2\text{O} = \text{Na}_2\text{CO}_3 + \text{H}_2\text{S}$
3.  $\text{CaSO}_4 + 2\text{C} = \text{CaS} + 2\text{CO}_2$
4.  $\text{MgSO}_4 + 2\text{C} = \text{MgS} + 2\text{CO}_2$
5.  $\text{Na}_2\text{SO}_4 + 2\text{C} = \text{Na}_2\text{S} + 2\text{CO}_2$

Within recent years geological studies, principally in the United States, have disclosed evidence of the reduction of sulphates with the concomitant development of hydrogen sulphide and of carbonates in the deeply buried waters of oil fields.<sup>1</sup> Somewhat similar conditions have been recognized by Siebenthal<sup>2</sup> in the Joplin zinc district of Missouri, Oklahoma, and Kansas, except that there the presence of hydrogen sulphide in the artesian waters has resulted in the precipitation of sulphides of the metals in sufficient amount to form ore deposits of great economic importance.

Although most of the equations here listed were originally written to express reactions recognized as due to living organisms, geologists concerned with the reduction of sulphates in connection with oil pools have assumed, not unnaturally, that sulphate-reducing organisms could not live under the conditions existing in the oil sands. They have postulated, therefore, that reactions of the types cited could proceed without the aid of living organisms.

In view of the great geologic importance of the natural reduction of sulphates, it has seemed desirable to examine critically the validity of the three postulates: (I) that sulphates may be reduced under surface or near surface conditions through the agency of living organisms, notably bacteria; (II) that sulphates may be reduced under conditions existing in nature by reactions like those cited without the aid of living organisms; (III) that living sulphate-reducing organisms do not and cannot exist in the waters found in oil sands.

<sup>1</sup> G. Sherburne Rogers, "The Sunset-Midway Oil Field, California," *U.S. Geol. Surv. Prof. Paper* 117, 1919.

<sup>2</sup> C. E. Siebenthal, "Origin of the Lead and Zinc Deposits of the Joplin Region," *U.S. Geol. Surv. Bull.* 606, 1915.

I. BIOCHEMICAL REDUCTIONS OF SULPHATES RECOGNIZED  
BY EARLIER OBSERVERS

In 1877 Pasteur presented to the French Academy of Sciences some notes by M. E. Plauchud on the natural decomposition of sulphates.<sup>1</sup>

A spring issuing from Tertiary rocks in Southeastern France is rich in hydrogen sulphide and on evaporation yields calcium sulphate. To the rocks and pebbles around the spring filamentous algae are attached in profusion. To determine whether the algae were instrumental in the formation of the hydrogen sulphide, M. Plauchud filled four flasks with lignite and other dead vegetal débris and with a filtered solution of calcium sulphate. After a month no trace of  $H_2S$  could be detected in these flasks. Eight flasks were filled with the filamentous algae and calcium sulphate solution. From all of these,  $H_2S$  was shortly obtained in abundance. Four flasks were filled with filamentous algae and calcium sulphate solution, but boiled three minutes before sealing. In these after more than a month no  $H_2S$  could be detected.

M. Plauchud concluded that the hydrogen sulphide owed its formation to the reduction of calcium sulphate by living organisms and that "dead organic matter does not suffice to produce this effect."

In a later communication<sup>2</sup> M. Plauchud confirmed his earlier results in a very ingenious manner. From a flask containing the living algae in a solution of calcium sulphate, he had been obtaining hydrogen sulphide at intervals for three months. He then anesthetized the algae with chloroform, and the evolution of  $H_2S$  promptly ceased. After a month the chloroform was evaporated and evolution of  $H_2S$  was resumed. He concludes that "these algae acting as a ferment are alone able to reduce the sulphates; this reduction never takes place through the agency of dead organic material."

In 1882 Etard and Oliver<sup>3</sup> found that some bacteria, the *Begiat-*

<sup>1</sup> "Recherches sur la formation des eaux sulfureuses naturelles," *Comptes Rendus*, Vol. LXXXIV (1877), pp. 235-38.

<sup>2</sup> "Sur la réduction des sulfates par les sulfuraires, et sur la formation des sulfures métalliques naturel," *ibid.*, Vol. XCV (1882), pp. 1362-65.

<sup>3</sup> A. Etard and L. Oliver, "De la réduction des sulfates par les êtres vivants," *ibid.*, pp. 846-49.

*toa*, common in lakes and the sea, abound especially in sulphurous waters. Microscopic examination revealed the presence of sulphur granules in their protoplasm. When these bacteria were grown in solutions free from sulphates, the sulphur granules disappeared but they were formed when the bacteria were grown in a solution of calcium sulphate. Filamentous blue algae of the genus *Oscillaria*, and green algae of the genus *Ulothrix*, were also found to decompose sodium and calcium sulphates with the formation of sulphur and hydrogen sulphide.

Equation 1 (p. 1271) was proposed by Hoppe-Seyler<sup>1</sup> in 1886. This investigator collected over mercury and analyzed the gases slowly evolved as the result of fermentation of bacterial slimes from rivers, bogs, and sewers. In an experiment extending over three years the gases from a flask carrying the following components were collected and analyzed:

|  | Grams  |
|--|--------|
| Filter paper (carrying 12.150 gm. of pure dry cellulose) . . . . | 13.090 |
| Gypsum (equivalent to 27.20 gm. of CaSO <sub>4</sub> ) . . . . . | 34.400 |
| Iron oxide (Fe <sub>2</sub> O <sub>3</sub> ) . . . . .           | 16.000 |

To this was added 910 cubic centimeters of distilled water and a small amount of river slime containing 0.2515 grams of organic and 0.7612 grams of inorganic matter.

CO<sub>2</sub> and CH<sub>4</sub> were the only gases that escaped from the flask. At the end of the experiment there was in the solution and in the precipitate combined only 12.73 grams of CaSO<sub>4</sub>. The remaining 14.47 grams had decomposed to yield CaCO<sub>3</sub> and FeS.

As indicated by the use of the word *Gährung* ("fermentation") in the title of his article, Hoppe-Seyler was aware that he was dealing with biochemical phenomena. His conclusion is significant (the italics are the writer's):

Both processes, namely, (1) the breaking down of cellulose to yield CO<sub>2</sub> and CH<sub>4</sub>, and (2) the reduction of CaSO<sub>4</sub> and Fe<sub>2</sub>O<sub>3</sub>, did not proceed independently of each other because *separately prepared methane reduces neither iron oxide nor calcium sulphate* and likewise paper does not interact with these bodies.<sup>2</sup>

<sup>1</sup> F. Hoppe-Seyler, "Über die Gährung der Cellulose mit Bildung von Methan und Kohlensäure," *Zeitschr. für physiolog. Chemie*, Vol. X (1886), pp. 401-40.

<sup>2</sup> *Op. cit.*, p. 437.

The Dutch bacteriologist, Beyerinck,<sup>1</sup> seems to have recognized more than any previous investigator the very considerable importance in nature of the bacterial reduction of sulphates. He suggested that the high H<sub>2</sub>S content of the waters of the Black Sea was due to sulphate-reducing bacteria, a suggestion that has since been fully verified.<sup>2</sup> He predicted, also, that the absence or extreme paucity

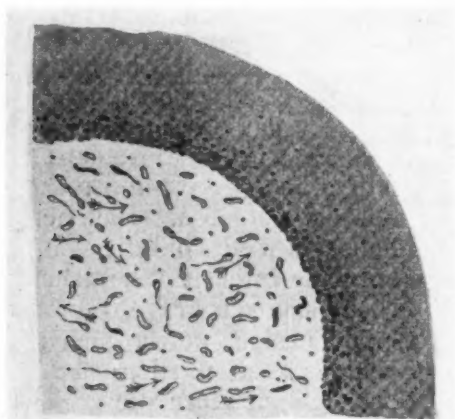


FIG. 1.—Portion of a colony of *Microspira desulfuricans* (Beyerinck). Black grains of iron sulphide occur between the bacteria and in the surrounding agar.

of sulphates in the deeper layers of the soil in certain parts of Holland would be found to be due to sulphate-reducing bacteria. The recent work of Kühr<sup>3</sup> has verified this prediction.

Beyerinck was the first to obtain pure cultures of sulphate-reducing bacteria and to describe and name such organisms. From ditch waters in Holland, he isolated an organism which he named *Spirillum desulfuricans* but which has since been called *Microspira*

<sup>1</sup> W. M. Beyerinck, "Über *Spirillum desulfuricans* als Ursache von Sulfat-Reduction," *Centralblatt für Bakteriologie* (Series II), Vol. I (1895), pp. 1-9 and 104-14.

<sup>2</sup> Issatchenko, "Sur la fermentation sulfhydrique dans la mer noire," *Comptes Rendus*, Vol. CLXXVIII (1924), p. 2204.

<sup>3</sup> C. A. H. von Wolzogen Kühr, "On the Occurrence of Sulphate Reduction in the Deeper Layers of the Earth" (in Eng.), *Koninklijke Akademie van Wetenschappen te Amsterdam, Proceedings*, Vol. XXV (1922), pp. 188-198.

*desulfuricans*. His drawing of this organism is reproduced in Figure 1. Through its agency at ordinary temperatures under anaerobic conditions, sulphates in solution were rapidly reduced with the liberation of  $H_2S$ .

The salt waters of the canals (Wadden) of the Dutch coastal tract are frequently high in  $H_2S$ , and their bottoms coated with muds which to a thickness of many meters are blackened by iron sulphide. Only a few millimeters of light-colored muds overlie the black mud. A. van Delden<sup>1</sup> proved that the  $H_2S$  in these waters was the result of bacterial reduction of sulphates and that the black iron sulphide was precipitated by the reaction of  $H_2S$  with iron salts in the water or the muds. He obtained pure cultures of the organism which he named *Microspira aestuarii* and differentiated from *Microspira desulfuricans* of Beyerinck. The two forms are indistinguishable morphologically, but *M. desulfuricans* is intolerant of sea water and *M. aestuarii* is intolerant of fresh water. Both are tolerant of brackish water ( $1\frac{1}{2}$  per cent NaCl). Both are strictly anaerobic. The presence of organic food in the culture media was essential as a source of energy for the sulphate reduction. The bacteria are highly tolerant of the  $H_2S$  resulting from their metabolism and in one case titration showed that 1,030 milligrams of  $H_2S$  per liter had been developed. The optimum temperature for the growth of *Microspira aestuarii* was 25°–30°C. The organism will take oxygen not only from sulphates from but sulphites, thiosulphates, and to a limited extent from nitrates. It is especially noteworthy that where oxygen diffused into the solid culture media, and only there, sulphur developed in minute droplets by the oxidation of  $H_2S$  to  $H_2O$  and S.

In 1907 Anton Rank<sup>2</sup> isolated and studied a strictly anaerobic sulphate reducing bacterium from canal slimes in Zurich. The microscopic appearance of this organism changed with age. In young cultures it assumed the form of short rods, and in older cultures showed longer *Spirillum* forms with as many as ten coils. The optimum temperature for its growth was about 25° C., but it grew also at 30° and

<sup>1</sup> "Beitrag zur Kenntnis der Sulfatreduktion durch Bakterien," *Centralblatt für Bakteriologie* (Ab. II), Vol. XI (1903–4), pp. 81–94 and 113–19.

<sup>2</sup> "Beiträge zur Kenntnis der sulfatreduzierenden Bakterien," *Inaugural-Dissertation der Universität Zürich*, 1907.

37°. It grew best in a medium with 3 per cent NaCl, but also grew in a medium containing no salt. It was capable of reducing not only sulphates but also thiosulphates and sulphites with the development of H<sub>2</sub>S. The organism was isolated from soils, sewage, river and ocean sands, and lake sand. He identified the bacterium with *Microspira desulfuricans* of Beyerinck and van Delden although only the young organisms corresponded in form with the descriptions published by these writers.

In 1921 Kühr<sup>1</sup> availed himself of the opportunity offered by the sinking of several new wells for the Amsterdam Waterworks in dune sands near a large canal to make bacterial tests on the materials traversed. The sands and intercalated clay layers from depths of 10 to 37 meters, the greatest depth examined, were gray to blue or bluish black from the presence of ferrous sulphide, and their contained waters were low or lacking in sulphates. Samples taken during the digging with due precautions against surface contamination showed the presence of sulphate-reducing bacteria, presumably *Microspira desulfuricans*.

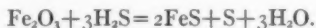
In 1895 Sir John Murray and Robert Irvine<sup>2</sup> reported some very important studies in the composition of sea water associated with the blue muds of the ocean bottom. These investigators, from a study of samples collected during the "Challenger" expedition, found that the waters of the blue muds departed notably from the remarkably uniform quality of the superficial waters of the ocean. The muds whose waters were investigated were all from depths of less than 16 fathoms, but muds of similar blue-black color occupy large areas on the ocean bottom from a few fathoms to, exceptionally, 2,900 fathoms. They are fine detritus from the land, colored dark by organic matter and sulphides of iron.

Careful analyses of the waters drained from the blue mud agree in showing that they are notably richer in the carbonate radicle and poorer in the sulphate radicle than the normal sea water from which they were derived. The gain in carbonate is approximately equiv-

<sup>1</sup> *Op. cit.*

<sup>2</sup> "On the Chemical Changes Which Take Place in the Composition of the Sea-Water Associated with Blue Muds on the Floor of the Ocean," *Trans. Roy. Soc. Edinburgh*, Vol. XXXVII (1895), pp. 481-508.

alent (in reacting value) to the loss in sulphate. Since the calcium content has not increased, it is evident that the gain in carbonate is not due to dissolving of calcium carbonate present in the muds, but is due to the reduction of sulphates by the organic matter in the muds and the subsequent decomposition of alkali or earth sulphides, by the carbonic acid thus formed to yield alkali or earth carbonates. The sulphur is deposited as iron sulphide through interaction with iron minerals in the muds and is thus permanently removed from solution. Generalized equations given to express the principal reactions are essentially equivalent to Nos. 3 and 1b of page 1271. The deposition of the sulphur is expressed by the equation:



Concerning the causes of these reactions, Murray and Irvine say:

This decomposition seems to be wholly due to the action of bacteria in causing putrefactive changes in dead organic matter. *We have found that if sea-water containing putrescible organic matter be sterilized by boiling, and thereafter care be taken to prevent ingress of bacteria to the cooled liquid, the changes above indicated do not take place.* Apparently the organic matter must be broken down by bacteria into its component elements, which in the nascent condition are capable of reducing sulphates to a lower form of combination.<sup>1</sup>

The observed decrease in sulphate ranged from 25 to 50 per cent. Iron sulphide originally deposited as FeS eventually became converted into pyrite.

In order to check the foregoing deductions experimentally, sea-water was allowed to stand in contact with mussel-flesh and sufficient ferric oxide to combine with all the sulphur as FeS. After a time the carbon and hydrogen of the organic matter had completely reduced the sulphates and the whole of the sulphur was found in combination with the iron as sulphide of iron (FeS), and the carbonic acid and ammonia formed by decay and deoxidation had increased the alkalinity which over all was equivalent to 4 grammes of carbonate of lime per liter, normal sea-water having an alkalinity of only 0.12 gramme.<sup>2</sup>

The extraordinary conditions existing in the Black Sea have been summarized by Sir John Murray<sup>3</sup> from the descriptions of Andrus-

<sup>1</sup> *Ibid.*, p. 498.

<sup>2</sup> *Ibid.*, p. 491.

<sup>3</sup> "On the Deposits of the Black Sea," *Scot. Geograph. Mag.*, Vol. XVI (1900), pp. 673-703.

son and others that are mainly in Russian. This sea, it may be remarked, owes its name to the abundance of black iron sulphide in its bottom muds. The sea attains a maximum depth of 7,236 feet and shows marked differences in density and salinity in its shallower and deeper portions. The mean surface salinity in the central parts of the sea is about 1.85 per cent, whereas in the deeper parts—from 2,400 to 6,600 feet—the salinity is about 2.25 per cent.<sup>1</sup> Below a depth of 750 feet the waters are essentially stagnant and contain too little dissolved air to support the ordinary forms of life. At 600 feet dissolved hydrogen sulphide begins to appear in significant amounts (about 30 cc. per liter) and increases in depth to the extraordinary concentration of 655 cubic centimeters per liter at 7,110 feet.

The identification by Zelinsky and Broussilovsky of bacterium *hydrosulfuricans ponticans* as the organism responsible for most of the hydrogen sulphide of the Black Sea is of doubtful validity. Nadson identified *hydrosulfuricans ponticans* with one of the commonest of the putrefactive bacteria—*Proteus vulgaris*—which is entirely incompetent to produce the extraordinary quantities of hydrogen sulphide present in this sea. Very recently Issatchenko,<sup>2</sup> who participated in Professor Knipovitch's Black Sea expedition, has studied a large number of mud samples dredged from depths as great as 2,118 meters. His bacteriological studies reveal the presence throughout this range in depth of a bacterium that directly and vigorously reduces sulphates. This bacterium which is strictly anaerobic he identifies with *Microspira aestuarii* of van Delden. The amount of H<sub>2</sub>S generated by this organism in laboratory cultures may reach 0.3 to 0.5 grams per liter. More detailed studies are in progress but it appears clear that the formation of H<sub>2</sub>S depends primarily on the presence of sulphates and that only small amounts of organic food material are essential as a source of energy.

Van Delden's experiments, it will be recalled, fixed the range of 25°–30° C. as the optimal temperature for the development of these forms. Of much interest is the recent discovery by L. Elion<sup>3</sup> of another

<sup>1</sup> Cf. with normal sea water at 3.5 per cent.

<sup>2</sup> *Op. cit.*, pp. 2204–6.

<sup>3</sup> "A Thermophilic Sulphate-reducing Bacterium," *Centralblatt für Bakteriologie* (Ab. II), Vol. LXIII (1924–25), pp. 58–67.

bacterium which he names *Vibrio thermodesulfuricans* that flourishes best at about 55° C. and appears to grow much more rapidly than *Microspira desulfuricans* and *M. aestuarii* though morphologically

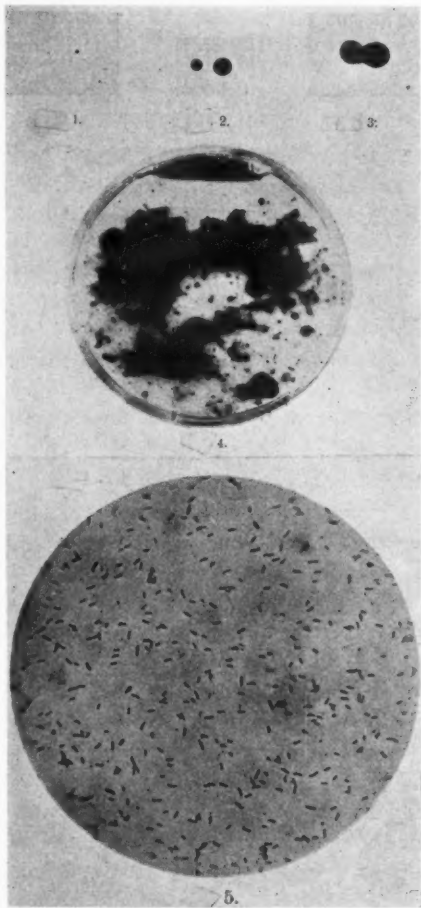


FIG. 2.—*Vibrio thermodesulfuricans* (Elion). A thermophilic sulphate-reducing bacterium from Holland. Optimal temperature about 55° C. 1, 2, and 3, two colonies, 1, 2, and 3 days, respectively, after inoculation; 4, coalescing colonies in agar; 5, parts of a colony stained with methylene blue and magnified 440 times.

indistinguishable from them (see Fig. 2). The velocity of growth diminishes above as well as below the optimal temperature.

A distinct formation of hydrogen sulphide is still noticeable between the superior limit of approximately  $65^{\circ}$ , and the inferior limit of about  $30^{\circ}$ . After a sojourn in a higher temperature, say  $80^{\circ}$ , if not prolonged too much, the bacterium will, however, not be killed off.

This bacterium was isolated from the mud of a ditch in Holland, dredged up at a time when the ditch was covered by thick ice. Its thermophilic character was therefore a surprise. Media inoculated with this bacterium showed profuse growths overnight. The bacterium is not spore bearing.

*Conclusions, Part I.*—It is clear from the foregoing examination of the literature that the reduction of sulphates noted by previous observers was in all instances attributed by them to living organisms, usually bacteria, but in some cases algae. Several observers reported their failure to obtain similar reductions with dead organic compounds.

Although many putrefactive bacteria decompose protein (which is sulphur bearing) with the formation of small amounts of  $H_2S$ , the vigorous reduction of sulphates to yield abundant  $H_2S$  is a function of another class of bacteria among which three apparently distinct forms have thus far been identified—*Microspira desulfuricans* (Beyrerinck), *M. aestuarii* (van Delden), and *Vibrio thermodesulfuricans* (Elion). These forms are morphologically very similar but thrive best under somewhat different conditions. *M. desulfuricans* is a fresh-water form but *M. aestuarii* thrives best in sea water. The optimum temperature for both ranges from  $25^{\circ}$  to  $30^{\circ}$  C. For *Vibrio thermodesulfuricans* the optimum temperature is about  $55^{\circ}$  C.

The situations in which sulphate-reducing bacteria have been found include river muds, brackish canal muds, sewerage, soils, lake sands, dune sands at depths to 37 meters, black muds of the ocean bottom to depths of 16 fathoms, and bottom muds of the Black Sea to depths of 2,118 meters. At these great depths in the Black Sea not only were the conditions highly anaerobic but the pressures were high, amounting to 3,000 pounds a square inch.

The modification of the composition of sea water by bacteria living in the bottom muds, as reported by Murray and Irvine, is

particularly noteworthy. The waters of the blue muds studied by these investigators were connate waters in the making. Further, they were being made under conditions analogous to those under which the source beds of petroleum are believed to have been deposited. Putrefaction of organic remains on the sea bottom is a process, therefore, capable of notably reducing the sulphate content of sea water at the time of its burial in the rocks. How deep and how long a burial is necessary to inhibit further bacterial action is uncertain, but in view of the 25 to 50 per cent reductions of sulphates observed by Murray and Irvine, complete loss of sulphates may not be uncommon. Connate waters associated with sediments rich in organic remains would, therefore, not be expected to have the composition of normal sea water, but to be characterized from the time of their burial by a lower sulphate content than normal sea water.

## II. POSSIBLE REDUCTION OF SULPHATES BY DEAD ORGANIC MATTER

*Experimental evidence.*—Although it is well known that some of the reactions cited on page 1271 can take place in the absence of organisms at high temperatures, no experimental evidence has thus far been recorded, so far as known to the writers, to show that they can proceed at the moderate temperatures that usually characterize oil-field waters. On the other hand, thermo-chemical considerations seem to be opposed to their progress at ordinary temperatures.

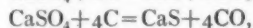
The validity of equation 1, for the reduction of  $\text{CaSO}_4$  by methane at ordinary temperatures, is brought into serious question by the work of Marino and Danesi,<sup>1</sup> who succeeded in obtaining this reduction only at high temperatures close to the explosion point for methane. At these temperatures some dissociation to  $\text{CaS}$  and  $\text{CaS}_2\text{O}_3$  took place.

The reduction of  $\text{CaSO}_4$  by carbon, as expressed by equation 3, has been investigated by Hofman and Mostowitsch.<sup>2</sup> Chemically pure calcium sulphate and sugar charcoal were used and the reduction carried on in a neutral atmosphere of nitrogen at atmospheric

<sup>1</sup> L. Marino and D. Danesi, *Gazz. Chim. Ital.*, Vol. XLIII, pp. 423-34.

<sup>2</sup> H. O. Hofman and W. Mostowitsch, "The Reduction of Calcium Sulphate by Carbon Monoxide and Carbon, and the Oxidation of Calcium Sulphide," *Trans. A.I.M.E.*, Vol. XLI (1910), pp. 763-85.

pressures. It was found that reduction began at 700° C. and was practically complete at 1,000° C. Both of the following equations are involved:



the proportions of CO<sub>2</sub> and CO varying with the temperature.

As pointed out by Palmer<sup>1</sup> the reaction of equation 5,



is the one involved in the Le Blanc process of soda manufacture, in which the mixture of sodium sulphate and charcoal is heated for a considerable period at 1,000° C. The reaction is strongly endothermic.

With regard to the reduction of ferrous sulphate by organic matter, Allen, Crenshaw, and Johnson<sup>2</sup> conclude:

Some experiments have been tried in this laboratory in the hope of "reducing" ferrous sulphate with organic matter, but the results have not been promising. The action of starch and glucose in aqueous solutions at 300° C. was either slight or nil. On the other hand, the possibilities of hydrogen sulphide are suggestive.

Some simple experiments were conducted by Bastin and Merritt to test further the possibilities of reduction of sulphates at ordinary room temperatures by coal, crude petroleum, and oil shales. Calcium sulphate and cupric sulphate, singly or together, were the sulphates chosen. The use of cupric sulphate, it should be noticed, insured aseptic conditions and eliminated any possibility of bacterial action. Furthermore, any development of hydrogen sulphide, or other soluble sulphide, would immediately have manifested itself by the precipitation of cupric sulphide. Hydrogen sulphide was further tested for with lead acetate, and carbonates were tested for by acidulation with hydrochloric acid. Most of the tests were continued over a period of 385 days. In no instance was there any evidence of reduction of sulphates or development of carbonates.

In addition, marsh gas, hydrogen, and acetylene were kept in

<sup>1</sup> Chase Palmer, "California Oil Field Waters," *Econ. Geol.*, Vol. XIX (1924), p. 628.

<sup>2</sup> "The Mineral Sulphides of Iron," *Amer. Jour. Sci.*, Vol. XXXIII (1912), p. 171.

contact with solutions of zinc, copper, sodium, and calcium sulphates for periods ranging from 60 to 112 days, with no reducing effects.

*Field evidence.*—That many natural brines in contact with petroleum are free from sulphates or carry them only in small amounts has been known since about 1874, but has been emphasized principally by the late G. Sherburne Rogers<sup>1</sup> in his studies in the Sunset-Midway oil field, California. He attributed the extremely low sulphate content of many of the deep waters there to the reducing action of certain components of the oil with which they were in contact, that is, the reducing agent was dead organic material.

The Sunset-Midway field consists of a succession of plunging anticlines of northwestward strike flanking the western side of the great structural trough marked by the San Joaquin Valley. The oil originated in the diatomaceous Miocene Maricopa shales but from them migrated in the main upward across and along an unconformity into the porous sandstones of the overlying Pliocene (?) Etche-goin formation, which contains the most important oil pools. Oil occurs on the crests and flanks of the anticlines and also on the monoclinical structure west of the anticlinal folds.

Upon the basis of seventy-five analyses, Rogers grouped the waters of the Sunset-Midway field into three classes, which he termed "normal," "modified," and "altered."

The "modified" waters are simple mixtures of the other types and need not further be considered.<sup>2</sup>

*Class I.*—The "normal" waters, which for convenience may be called Class I, comprise the surface or near-surface waters from all parts of the oil field. These are fresh to brackish waters of low concentration in which the reacting value of sulphate by percentage is high, ranging from 11.2 to 43.6, and the concentration from 309 to 8,790 p.p.m. Out of sixteen analyses given by Rogers, Nos. 2, 20, and 21 (see Fig. 3) are selected as representative, but there is large variability within the class.

<sup>1</sup> "The Sunset-Midway Oil Field, California," *U.S. Geol. Surv. Prof. Paper 117*, 1919.

<sup>2</sup> In all the diagrams of this paper showing water composition, reacting values in percentage as computed by Palmer's method (see Bull. 479, U.S. Geol. Survey), are plotted for the principal radicles or groups of radicles, basic radicles in one column and acid in the other. A solid line shows the concentration or "total solids" in parts per million.

**Class II.**—The "altered" waters are so called because they are poor or lacking in sulphates as a result of chemical alteration. Two classes of "altered" waters are recognized which may be termed

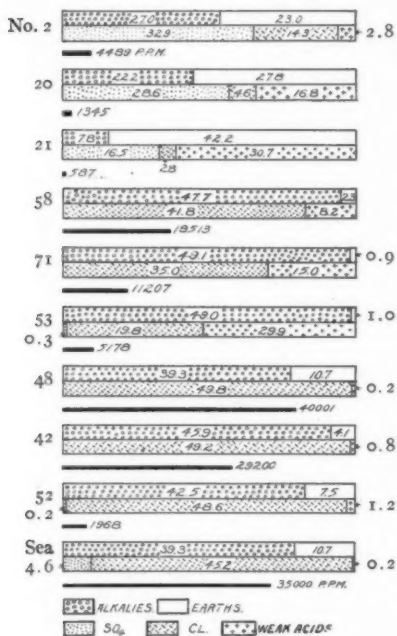


FIG. 3.—Graphs of waters from the Sunset-Midway oil field, Calif., showing reacting values of principal components in percentage and concentration in parts per million (heavy black line). Numbers correspond to those in Roger's report. Dittmar's average for sea water is shown for comparison.

30,000 p.p.m. The average concentration of sea water is about 35,000 p.p.m.

**Class III** includes altered waters that are alkaline rather than saline, and free or nearly free from sulphates. They are edge waters, or top waters, from wells in the western part of the field. They are intermediate in concentration between Classes I and II, ranging from

Classes II and III. The waters of Class II are the brines associated with the oil throughout the central and eastern part of the field. A comparison with the graph of Dittmar's average sea water (see Fig. 3) shows how closely these waters resemble sea water, the main contrast being the absence of sulphate. The maximum reacting value of sulphate in the twenty analyses was 0.3 per cent. Out of twenty analyses, Nos. 48, 52, and 42, representing maximum, intermediate, and minimum reacting values of the earths, are shown (see Fig. 3). The small variability in the proportions of the components within this class of waters is apparent. The concentration varies greatly ranging from 1,968 to 44,732 p.p.m., but is usually above

2,800 to 18,500 p.p.m. Out of twenty-eight analyses, Nos. 53, 58, and 71 representing maximum, intermediate, and minimum reacting values of the weak acids, are selected (see Fig. 3). The small variability within the class is apparent.

Class II is typical of waters commonly regarded by geologists as "connate," that is, as water buried with sediments and subsequently little modified in composition, though often changed in concentration. They may have migrated under ground from sediments with which they were buried to neighboring formations, but there is no evidence that they have ever mixed notably with ordinary meteoric waters. Their low sulphate content was interpreted by Rogers as due to the direct reducing effect of the hydrocarbons of petroleum.

The alkaline waters of Class III are interpreted by Rogers as resulting from the mixing of the "normal" waters of meteoric origin, Class I, with the waters of Class II, plus chemical modification through contact with the oil. As with the "brines," the low sulphate content is attributed to the reducing action of some components, as yet undetermined, of the petroleum.

In the "normal" waters of Class I and in the waters of Class II (see Fig. 3) the reacting value of the strong acid radicles exceeds that of the alkalies. In the waters of Class III, on the contrary, the reacting value of the alkalies exceeds that of the strong acid radicles, and the waters are therefore alkaline in quality. This reversal implies reduction of sulphates with the concomitant development of carbonates and of  $H_2S$  or other sulphides.  $H_2S$  now accompanies some of the low sulphate waters of the Sunset-Midway field. Reduction of alkali-earth sulphates with the development of equivalent amounts of alkali-earth carbonates formed part of the process but could at most only bring the alkalies and strong acid radicles into equality; the excess of alkalies over strong acid radicles in the modified waters implies, in addition, the reduction of alkali sulphates.

*Conclusions, Part II.*—From this review it may be concluded that thus far no experimental evidence has been obtained of the reduction of sulphates at ordinary temperatures by dead organic matter, although such reductions do take place at high temperatures.

**Class II.**—The "altered" waters are so called because they are poor or lacking in sulphates as a result of chemical alteration. Two classes of "altered" waters are recognized which may be termed

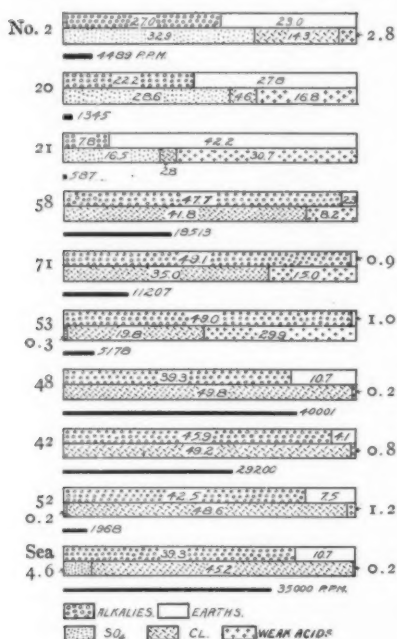


FIG. 3.—Graphs of waters from the Sunset-Midway oil field, Calif., showing reacting values of principal components in percentage and concentration in parts per million (heavy black line). Numbers correspond to those in Roger's report. Dittmar's average for sea water is shown for comparison.

30,000 p.p.m. The average concentration of sea water is about 35,000 p.p.m.

**Class III** includes altered waters that are alkaline rather than saline, and free or nearly free from sulphates. They are edge waters, or top waters, from wells in the western part of the field. They are intermediate in concentration between Classes I and II, ranging from

Classes II and III. The waters of Class II are the brines associated with the oil throughout the central and eastern part of the field. A comparison with the graph of Dittmar's average sea water (see Fig. 3) shows how closely these waters resemble sea water, the main contrast being the absence of sulphate. The maximum reacting value of sulphate in the twenty analyses was 0.3 per cent. Out of twenty analyses, Nos. 48, 52, and 42, representing maximum, intermediate, and minimum reacting values of the earths, are shown (see Fig. 3). The small variability in the proportions of the components within this class of waters is apparent. The concentration varies greatly ranging from 1,968 to 44,732 p.p.m., but is usually above

2,800 to 18,500 p.p.m. Out of twenty-eight analyses, Nos. 53, 58, and 71 representing maximum, intermediate, and minimum reacting values of the weak acids, are selected (see Fig. 3). The small variability within the class is apparent.

Class II is typical of waters commonly regarded by geologists as "connate," that is, as water buried with sediments and subsequently little modified in composition, though often changed in concentration. They may have migrated under ground from sediments with which they were buried to neighboring formations, but there is no evidence that they have ever mixed notably with ordinary meteoric waters. Their low sulphate content was interpreted by Rogers as due to the direct reducing effect of the hydrocarbons of petroleum.

The alkaline waters of Class III are interpreted by Rogers as resulting from the mixing of the "normal" waters of meteoric origin, Class I, with the waters of Class II, plus chemical modification through contact with the oil. As with the "brines," the low sulphate content is attributed to the reducing action of some components, as yet undetermined, of the petroleum.

In the "normal" waters of Class I and in the waters of Class II (see Fig. 3) the reacting value of the strong acid radicles exceeds that of the alkalies. In the waters of Class III, on the contrary, the reacting value of the alkalies exceeds that of the strong acid radicles, and the waters are therefore alkaline in quality. This reversal implies reduction of sulphates with the concomitant development of carbonates and of  $H_2S$  or other sulphides.  $H_2S$  now accompanies some of the low sulphate waters of the Sunset-Midway field. Reduction of alkali-earth sulphates with the development of equivalent amounts of alkali-earth carbonates formed part of the process but could at most only bring the alkalies and strong acid radicles into equality; the excess of alkalies over strong acid radicles in the modified waters implies, in addition, the reduction of alkali sulphates.

*Conclusions, Part II.*—From this review it may be concluded that thus far no experimental evidence has been obtained of the reduction of sulphates at ordinary temperatures by dead organic matter, although such reductions do take place at high temperatures.

Future investigations may, of course, show that some of them can proceed at ordinary temperatures at very slow rates.

Sulphate reduction accomplished within the oil-bearing sediments appears to be the only plausible explanation of the essential absence of sulphates from many of the brines associated with petroleum, but thus far no evidence has been presented to show whether the reduction was accomplished by dead organic matter or by living organisms. The purpose of the next section of this paper will be to present the results of researches covering this important point.

### III. SULPHATE-REDUCING BACTERIA IN OIL-FIELD WATERS

The field data presented by Rogers are very convincing as to the fact of sulphate reduction in oil fields but the explanation offered by him—the reducing action of the dead organic matter of the oil—is in conflict with the experimental evidence cited in the previous section. It seemed desirable, therefore, to test the waters from some oil fields to determine whether the tacit assumption of the absence in them of sulphate-reducing bacteria was correct.

Through the courtesy of Dr. M. M. Leighton, chief of the Illinois Geological Survey, an opportunity was provided to collect samples of waters from several oil-bearing horizons in Illinois. In this work there was enlisted the co-operation of Mr. Gail Moulton, of the State Survey, who had in hand a comprehensive study of the oil-field waters of Illinois and was familiar with their occurrence.

All water samples collected from the Illinois oil fields were submitted to bacteriological study within a few days of their collection, in the Bacteriological Laboratory of the University of Chicago. Dr. Frank E. Greer, who undertook their examination, has been engaged for some time in a study of those bacteria capable of reducing sulphites with the formation of hydrogen sulphide, so that the extension of the study, with modified technique, to sulphate reduction, was a step readily accomplished.

Subsequently, through the support of the Research Committee of the American Association of Petroleum Geologists, Dr. Edson S. Bastin was enabled to extend the bacterial studies of the Sunset-

Midway and Coalinga oil fields, California. In the California work the co-operation of Dr. Belle G. Anderson, of the Department of Bacteriology of the University of California, was enlisted in making the cultures. The field work was facilitated by the generous co-operation and hospitality of the officials of the Standard and Pacific Oil companies in California.

*Methods of collecting samples.*—Samples were taken in 8-ounce ground-glass stoppered bottles which had previously been sterilized in the bacteriological laboratory. A piece of cloth was tied over the top of the bottle. The samples were mixtures of oil and water constituting the regular yield of wells most of which had been pumping continuously for days, weeks, or months. All samples were taken from as near the head of the well as possible. In the Illinois fields most of them were taken from the pump jacks by removing or loosening a bleeder-nut allowing the oil and water to spurt freely for a few minutes and then filling the bottle. In the California fields only a few of the wells had bleeder pipes at the head of the well and many samples had to be taken from the pipes leading from the well to troughs or tanks. A few samples had to be taken from gas traps.

The bottles were opened only long enough to collect the sample, and were then securely stoppered and tied. Inoculations were made within a few days after collecting.

*Methods of inoculation.*—Either in the field or in the laboratory, the waters were tested qualitatively for sulphates with barium chloride, for hydrogen sulphide with lead acetate, and for alkalinity with phenolphthalein.

Two basic culture media in eight modifications were used as shown on page 1288.

Medium 1 is essentially that which van Delden found most suitable. Both liquid and solid media were used. Following the method used by earlier investigators by the addition of small amounts of a soluble ferrous salt which served as an "indicator," the presence of sulphate-reducing bacteria was readily detected. Through the bacterial reduction of the sulphates,  $H_2S$  is generated which reacts with the iron salts to form ferrous sulphate,  $FeS$ . In the liquid media this appeared as a black precipitate, often clinging to filamentous

bacterial growths. In the solid media it colors the spherical colonies black. Characteristic appearances of liquid and solid cultures are shown in Figure 4.

All water samples carrying enough  $H_2S$  so that they blackened the media by direct inorganic precipitation on inoculation were placed in a sterile vacuum dessicator and the  $H_2S$  removed by evacuation before the inoculations were made, or a vacuum pump was used.

|  | Grams   |
|--|---------|
| Medium 1.1— $K_2HPO_4$ .....               | 0.5     |
| Asparagin.....                             | 1.0     |
| Magnesium sulphate.....                    | 2.5     |
| Sodium lactate.....                        | 5.0     |
| Mohr's salt (ferrous ammonium sulphate)... | Trace   |
| Distilled water.....                       | 1 liter |
| Medium 1.2—Same as 1.1 with 30 gm. NaCl    |         |
| Medium 1.3—Same as 1.1 with 30 gm. agar    |         |
| Medium 1.4—Same as 1.2 with 30 gm. agar    |         |
|  | Grams   |
| Medium 2.1— $K_2HPO_4$ .....               | 0.5     |
| Ammonium sulphate.....                     | 2.0     |
| Sodium sulphate.....                       | 2.0     |
| Iron lactate.....                          | 5.0     |
| Distilled water.....                       | 1 liter |
| Medium 2.2—Same as 2.1 with 30 gm. NaCl    |         |
| Medium 2.3—Same as 2.1 with 30 gm. agar    |         |
| Medium 2.4—Same as 2.2 with 30 gm. agar    |         |

The media were tubed in large test-tubes and sterilized in the autoclave at 15-pound pressure for 20 minutes. All media were heated in the Arnold before use to expel air from liquid media and to melt solid media. All were cooled to about 45° or 50° C. before inoculating. Each tube was inoculated with 10 cubic centimeters of water sample. Duplicates of each type of medium were inoculated. All liquid media were sealed with sterile vaseline. Incubation at 37° C.

The details of field occurrence and of laboratory results are given in Table I, but the essential features will be separately summarized for Illinois and for California. Tabulated results refer only to sulphate-reducing bacteria although in some waters other bacteria were also present.

*Summary of results in Illinois.*—In selecting wells for sampling, those yielding hydrogen sulphide and waters low in sulphates were

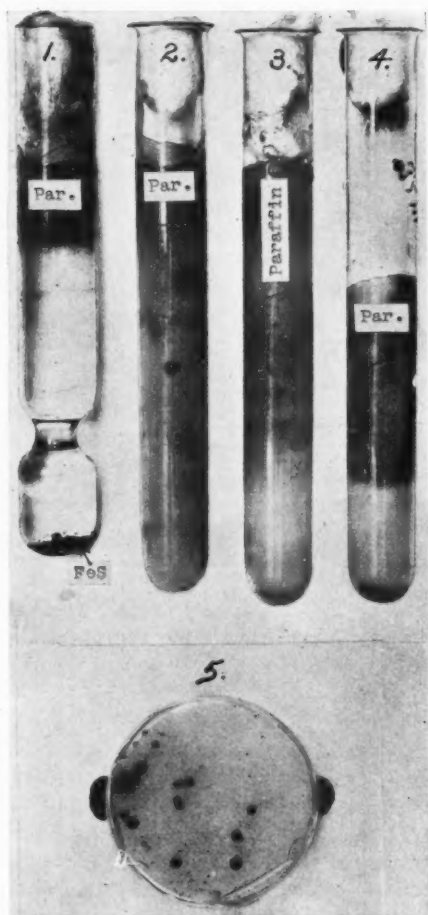


FIG. 4.—Cultures of sulphate-reducing bacteria from Illinois oil-field waters. No. 1 is in a liquid medium, and the  $\text{FeS}$  resulting from the bacterial action appears as a black precipitate. Nos. 2-4 are solid media in which the bacteria form black colonies. In No. 4 the tube is partly filled with a black mass of coalescing colonies. No. 5 is a Petridish culture in solid medium.

TABLE I  
ILLINOIS OIL-FIELD WATERS

| Sample No. | Result* | Well                            | Company                    | County   | Twp.                            | Section  | Depth in Feet | Producing Horizon                     | H <sub>2</sub> S | Temp. °C. | Analysis Available (M = in Progress) |
|------------|---------|---------------------------------|----------------------------|----------|---------------------------------|----------|---------------|---------------------------------------|------------------|-----------|--------------------------------------|
| 1....      | ++      | A. J. Bigelow, No. 10           | Ohio Oil Co.               | Clark    | Parker                          | 6 NE. 1  | 473           | "Mississippi lime" plus Pennsylvanian | +                | .....     | +                                    |
| 2....      | ++      | R. E. Deverick, Acct. 2, Well 4 | Ohio Oil Co.               | Clark    | Johnson                         | 26 SW. 1 | 640           | Pennsylvanian (Carbondale)            | +                | .....     | +                                    |
| 3....      | ++      | K. and E. Young, No. 43         | Ohio Oil Co.               | Clark    | Parker                          | 18       | 542           | Mississippian (Spergen-St. Louis)     | +                | .....     | Adjacent Well 48                     |
| 4....      | ++      | Drake Heirs, No. 13             | Ohio Oil Co.               | Clark    | Westfield                       | 32 SE. 1 | 510           | Mississippian (Spergen-St. Louis)     | +                | .....     | +                                    |
| 5....      | ++      | M. Partlow, Acct. 2, Well 12    | Ohio Oil Co.               | Clark    | Johnson                         | 34 NE. 1 | 579           | Pennsylvanian (Carbondale)            | +                | 24°       | +                                    |
| 6....      | ++      | Nora A. Fox, No. 12             | Ohio Oil Co.               | Clark    | Johnson                         | 34 NE. 1 | 562           | Pennsylvanian (Carbondale)            | +                | .....     | Adjacent Well 9                      |
| 7....      | ++      | C. A. Fuller, Acct. 2, Well 26  | Ohio Oil Co.               | Clark    | Parker                          | 5 SW. 1  | 500±          | Spergen-St. Louis                     | +                | .....     | Adjacent Well 25                     |
| 8....      | ++      | R. E. Deverick, Acct. 2, Well 9 | Ohio Oil Co.               | Clark    | Johnson                         | 26 SW. 1 | 649           | Pennsylvanian (Carbondale)            | +                | .....     | +                                    |
| 9....      | ++      | John Carper, No. 1              | Trenton Rock Oil & Gas Co. | Clark    | T. 10 N., R. 13 W. Martinsville | 30 NW. 1 | 1,600         | Devonian                              | -                | .....     | +                                    |
| 10....     | ++      | Barr, No. 4                     | Ellis & Myers Co.          | Clark    | T. 10 N., R. 13 W. Martinsville | 30 NW. 1 | 1,390         | Mississippian (Carper sand)           | +                | .....     | M                                    |
| 11....     | ++      | Barr, No. 2                     | Ellis & Myers Co.          | Clark    | T. 10 N., R. 13 W.              | 30 NE. 1 | 1,582         | Top of Devonian ls.                   | -                | .....     | M                                    |
| 12....     | +       | Knecht, No. 7                   | J. Campbell Co.            | Clark    | T. 11 N., R. 14 W. Parker       | 32 SE. 1 | 400           | Top of Mississippian ls.              | -                | .....     | M                                    |
| 13....     | +       | Bridgeport-Marcotte, No. 2      | W. C. McBride, Inc.        | Wabash   | T. 1 N., R. 12 W.               | 24       | 1,115         | Pennsylvanian (Bridgeport)            | -                | .....     | M                                    |
| 14....     | ++      | Laura Gillespie No. 22          | Big Four Oil Co.           | Lawrence | Dennison                        | 26       | 1,255         | Pottsville (Buchanan sand)            | -                | .....     | +                                    |
| 15....     | ++      | Laura Gillespie No. 4           | Big Four Oil Co.           | Lawrence | Dennison                        | 26       | 975           | Upper Pottsville                      | -                | .....     | +                                    |
| 16....     | +       | Ed. Meagher, No. 4              | Ohio Oil Co.               | Lawrence | Dennison                        | 5        | 1,866         | Mississippian (McCloskey sand)        | +                | .....     | +                                    |
| 17....     | -       | Barnett, No. 11                 | Ohio Oil Co.               | Lawrence | Dennison                        | 8        | 1,601         | Mississippian (Kirkwood sand)         | -                | .....     | +                                    |
| 18....     | ++      | J. W. Baud, No. 7               | Ohio Oil Co.               | Crawford | Honey Creek                     | 36       | 1,040         | Pennsylvanian                         | +                | .....     | M                                    |
| 19....     | +       | J. W. Baud, No. 1               | Ohio Oil Co.               | Crawford | Honey Creek                     | 36       | 960-75        | Pennsylvanian (Robinson sand)         | +                | .....     | .....                                |
| 20....     | +       | J. W. Baud, No. 4               | Ohio Oil Co.               | Crawford | Honey Creek                     | 36       | 982           | Pennsylvanian (Robinson sand)         | +                | .....     | M                                    |
| 21....     | +       | Henry Parker, No. 50            | Ohio Oil Co.               | Crawford | Honey Creek                     | 15       | 1,032         | Pennsylvanian                         | +                | .....     | .....                                |
| 22....     | +       | Henry Parker, No. 33            | Ohio Oil Co.               | Crawford | Honey Creek                     | 15       | 1,011         | Pennsylvanian                         | +                | .....     | .....                                |
| 23....     | -       | Henry Parker, No. 27            | Ohio Oil Co.               | Crawford | Honey Creek                     | 15       | 1,011         | Pennsylvanian                         | +                | .....     | M                                    |
| 24....     | ++      | Henry Parker, No. 9             | Ohio Oil Co.               | Crawford | Honey Creek                     | 15       | 1,017         | Pennsylvanian                         | +                | .....     | M                                    |
| 25....     | +       | John Acker, No. 4               | Pure Oil Co.               | Monroe   | T. 2 S., R. 10 W.               | 2 SW. 1  | 435           | "Trenton" (Kimmswick)                 | -                | .....     | +                                    |
| 26....     | +       | H. Kolmer, No. 6                | Ohio Oil Co.               | Monroe   | T. 2 S., R. 10 W.               | 2 NE. 1  | 467           | "Trenton" (Kimmswick)                 | +                | .....     | +                                    |
| 27....     | ++      | A. Gaertner, No. 5              | Ohio Oil Co.               | Monroe   | T. 2 S., R. 10 W.               | 2 NW. 1  | 475±          | "Trenton" (Kimmswick)                 | +                | .....     | +                                    |
| 28....     | ++      | Gummershiemer, Acct. 1, Well 3  | Ohio Oil Co.               | Monroe   | T. 2 S., R. 10 W.               | 3 NE. 1  | 475±          | "Trenton" (Kimmswick)                 | +                | .....     | +                                    |
| 29....     | ++      | A. Gaertner, No. 3              | Ohio Oil Co.               | Monroe   | T. 2 S., R. 10 W.               | 2 NW. 1  | 429           | "Trenton" (Kimmswick)                 | +                | .....     | +                                    |
| 30....     | ++      | Gummershiemer, Acct. 2, Well 3  | Ohio Oil Co.               | Monroe   | T. 2 S., R. 10 W.               | 3 NE. 1  | 475±          | "Trenton" (Kimmswick)                 | +                | .....     | +                                    |

\* In this column one plus sign indicates slight or moderate reduction of sulphates; two plus signs, vigorous reduction. Minus sign indicates no reduction.

TABLE I—Continued  
ILLINOIS OIL-FIELD WATERS

| Sample No. | Black Precipitates of FeS in Liquid Media  | Black Colonies in Solid Media   | Remarks  |
|------------|--|---|--|
| 1.....     | 2d day, med. 1.1 moderate; med. 1.2 abundant   | 6th day, med. 1.3 coalescing colonies fill tube; med. 2.3 a few small colonies  | Constantly pumping; oil-water ratio, about 1:40              |
| 2.....     | 2d day, med. 1.1 and 1.2 abundant  | 2d day, med. 1.3 coalescing colonies nearly fill tube; med. 2.3, coalescing colonies fill two-thirds of tube  | Constantly pumping; oil-water ratio, about 1:10              |
| 3.....     | 2d day, med. 1.1 and 1.2 abundant, filamentous   | 2d day, med. 1.3 nearly filled with coalescing colonies; med. 2.3 lower two-thirds filled with coalescing colonies  | Pumping half-time; 100 bbls. oil per day                     |
| 4.....     | 2d day, med. 1.1 moderate; med. 1.2 abundant   | 2d day, med. 1.3 nearly filled with coalescing colonies. 6th day, med. 2.3 many black colonies  | 400 bbls. oil per day  |
| 5.....     | 2d day, med. 1.1 and 1.2 abundant, filamentous   | 2d day, med. 1.3 two-thirds filled with coalescing colonies   | Constantly pumping; oil-water ratio, about 1:10              |
| 6.....     | 2d day, med. 1.1 moderate; med. 1.2 abundant, filamentous  | 2d day, med. 1.3 and 2.3 three-fourths filled with coalescing colonies  |  |
| 7.....     | 2d day, med. 1.1 moderate; med. 1.2 moderate, filamentous. 6th day, med. 1.1 and 1.2 abundant      | 2d day, med. 1.3 three-fourths filled with coalescing colonies; med. 2.3 coalescing colonies fill tube  |  |
| 8.....     | 2d day, med. 1.1 slight; med. 1.2 moderate. 6th day, med. 1.1 and 1.2 abundant                     | 2d day, med. 1.3 three-fourths filled with coalescing colonies  |  |
| 9.....     | 4th day, med. 1.1 slight; med. 1.2 abundant  | Not used  | Taste, salty   |
| 10.....    | 2d day, med. 1.2 slight. 4th day, med. 1.1 moderate; med. 1.2 abundant                             | Not used  | Pumping mainly water; taste, salty                           |
| 11.....    | 4th day, med. 1.1 moderate; med. 1.2 abundant  | Not used  | Taste, salty   |
| 12.....    | 4th day, med. 1.1 and 1.2 slight; 8th day, med. 1.1 and 1.2 abundant                               | Not used  | Taste, slightly salty; no precipitate with BaCl <sub>2</sub> |
| 13.....    | 4th day, med. 1.1 moderate; 8th day, med. 1.1 and 1.2 moderate                                     | Not used  | BaCl <sub>2</sub> shows abundant sulphates                   |
| 14.....    | 6th day, med. 1.1 abundant; med. 1.2 and 2.1 slight  | 6th day, med. 1.3 coalescing colonies fill tube   | Continuously pumping; cased to 1,161 ft.                     |
| 15.....    | 8th day, med. 1.1 slight; med. 1.2 moderate  | Negative  | Continuously pumping; cased to 910 ft.                       |
| 16.....    | 3d day, med. 1.1 abundant; med. 1.2 moderate   | 4th day, med. 2.3 two colonies  | Pumping 3½ hrs. when sampled; cased to 1,783 ft.             |
| 17.....    | Negative   | Negative  | Continuously pumping   |
| 18.....    | 3d day, med. 1.1 abundant; med. 1.2 slight. 10th day, med. 1.2 abundant                            | 3d day, med. 1.3 many colonies; med. 2.3 five colonies. 10th day, med. 1.3 coalescing colonies fill tube; med. 2.3 coalescing colonies two-thirds fill tube     | Continuously pumping; corrodes pipes; cased to 967 ft.       |
| 19.....    | 8th day, med. 1.1 slight; 10th day, med. 1.1 moderate  | 10th day, med. 1.3 four colonies  | Continuously pumping; corrodes pipes                         |
| 20.....    | 3d day, med. 1.1 moderate; 10th day, no notable increase   | Negative  | Continuously pumping; corrodes pipes; cased to 445 ft.       |
| 21.....    | 4th day, med. 1.1 moderate; 10th day, no notable increase  | Negative  | Continuously pumping; corrodes pipes; cased to 900 ft.       |
| 22.....    | Negative   | 7th day, med. 1.3 a few colonies  | Continuously pumping; corrodes pipes; cased to 928 ft.       |
| 23.....    | Negative   | Negative  | Continuously pumping; corrodes pipes; cased to 944 ft.       |
| 24.....    | 3d day, med. 1.1 and 1.2 moderate; 7th day, med. 1.1 and 1.2 abundant                              | 3d day, med. 1.3 and 2.3 coalescing colonies fill tube  | Continuously pumping; corrodes pipes; cased to 920 ft.       |
| 25.....    | 4th day, med. 1.1 slight; 9th day, med. 1.1 moderate   | Negative  |  |
| 26.....    | 4th day, med. 1.2 slight   | 9th day, med. 1.3 one colony; med. 2.3 coalescing colonies fill tube  | Oil-water ratio, 1:9   |
| 27.....    | 4th day, med. 1.1 slight. 9th day, med. 1.2 slight; med. 2.1 abundant. 10th day, med. 1.1 moderate | 4th day, med. 1.3 several colonies; med. 2.3 coalescing colonies half fill tube   | Oil-water ratio, 1:9   |
| 28.....    | 4th day, med. 1.1 and 1.2 slight. 9th day, med. 2.1 abundant. 13th day, med. 1.1 and 1.2 abundant  | 4th day, med. 1.3 abundant colonies. 9th day, colonies coalesced to fill tube   | Oil-water ratio, 1:10  |
| 29.....    | 4th day, med. 1.1 moderate. 9th day, med. 1.2 moderate; med. 2.1 abundant                          | 4th day, med. 2.3 coalescing colonies partly fill tube. 9th day, med. 1.3 several coalescing colonies. 13th day, med. 1.3 and 2.3 coalescing colonies fill tube | Oil-water ratio, 1:16; constantly pumping                    |
| 30.....    | 4th day, med. 1.1 moderate. 9th day, med. 1.2 abundant   | 9th day, med. 2.3 several colonies. 13th day, med. 2.3 at least 15 colonies   | Oil-water ratio, 1:18  |

usually chosen. Out of the thirty wells sampled only two showed no sulphate-reducing bacteria. In nineteen they appeared to be abundant (Fig. 5). The depths of the wells giving positive results ranged from 400 to 1,866 feet. The producing horizons were Pennsylvanian, Mississippian, and Silurian along the La Salle anticline in south

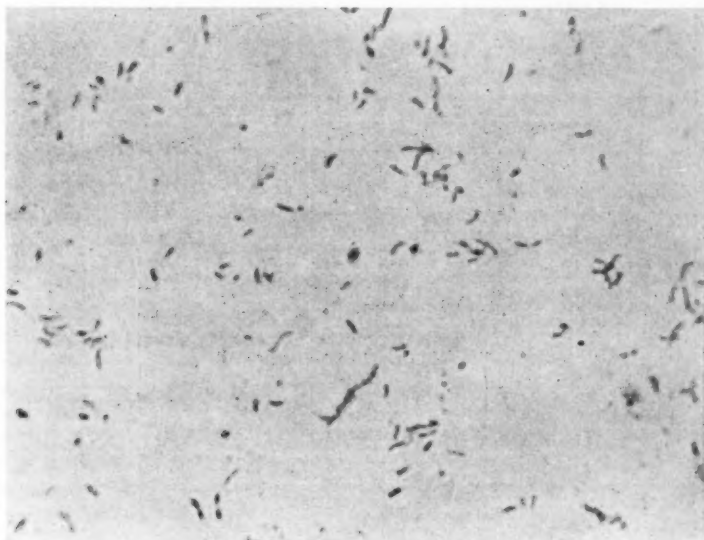


FIG. 5.—A sulphate-reducing bacterium, probably *Microspira aestuarii* (van Delden), isolated from Illinois oil-field waters. Magnified 1,800 times.

eastern Illinois (Wabash, Clark, and Crawford counties) and Ordovician in the Waterloo field of southwestern Illinois (Monroe Co.).

For the twenty-four wells sampled in southeastern Illinois, water analyses are available for eight, and for three others analyses from closely contiguous wells producing from the same horizons are available. The concentration of these waters is quite variable, the total solids ranging from 13,470 to 63,980 parts per million, the concentration of sea water being about 35,000. In quality, however, that is, the relative proportions of their dissolved components, they show remarkably little variation. The analyses of Samples 1, 5, and 16

are selected as representative (see Fig. 6); their similarity in quality to normal sea water is apparent and because of this similarity they would be classed as "connate" waters. Sample 15, whose diagram is also shown, is the only notable variant within this group of analyses; this water is slightly alkaline.

For the six samples from the Waterloo field in southwestern Illinois, five analyses are available. These waters are prevailingly of lower concentration than those just described, ranging from 7,295 to 15,560 parts per million. They differ also from the south eastern Illinois waters in quality, being characterized by a larger proportion of alkaline earths. Samples 25, 27, and 29 are representative (see Fig. 6).

*Summary of results in California.*—About one full day was spent in the Sunset-Midway field. Samples were taken at the localities shown in Figure 7. One sample was also taken in the Elk Hills near the eastern limit of the

field. The only sample of surface water obtainable (No. 37, Table II) was taken at the water works along the main highway from Taft to Bakersfield. It carried no sulphate-reducing bacteria.

The source beds in this field are the diatomaceous Maricopa shales of Miocene age. Four samples were taken of waters from the Maricopa shales: two from water wells (Nos. 32 and 34) and two from oil wells (Nos. 31 and 33)—all carried sulphate-reducing bacteria. The main producing horizon is the Echegoin formation (Pliocene).

Of the nine samples that carried sulphate-reducing bacteria,

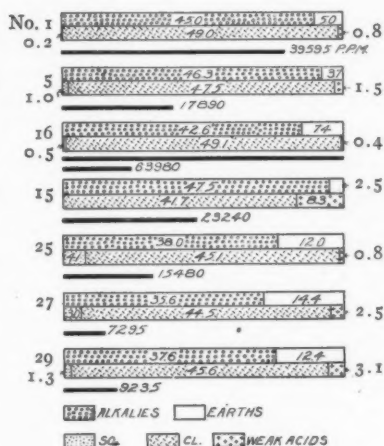


FIG. 6.—Graphs of Illinois oil-field waters. Components plotted in terms of reacting values in percentage according to Palmer's system. Concentration in parts per million shown by heavy black lines.

TABLE II  
CALIFORNIA OIL-FIELD WATERS

| Sample No. | Re-<br>sults* | Well No.                               | Company                   | County | Twp.<br>and<br>Range  | Sec-<br>tion | Depth<br>in<br>Feet | Temp.<br>° C. | Producing<br>Horizon  | H/S | Analysis             |
|------------|---------------|--|---------------------------|--------|-----------------------|--------------|---------------------|---------------|---|-----|----------------------|
| 1...       | +             | 3                                      | Pacific Oil Co.           | Fresno | T. 20 S.,<br>R. 12 E. | 25           | 1,460               | 32            | Jacalitos formation<br>(Miocene)                              | ?   | +<br>(1924)          |
| 2...       | +             | 36                                     | Pacific Oil Co.           | Fresno | T. 20 S.,<br>R. 15 E. | 19           | 2,960               | 37            | Jacalitos formation<br>(Miocene)                              | -   | +<br>(1921)          |
| 3...       | ++            | 38                                     | Pacific Oil Co.           | Fresno | T. 20 S.,<br>R. 15 E. | 19           | 3,090               | 42            | Jacalitos formation<br>(Miocene)                              | -   | +<br>(1921)          |
| 4...       | ++            | 4                                      | American<br>Petroleum Co. | Fresno | T. 20 S.,<br>R. 15 E. | 18           | About<br>1,300      | 34            | Jacalitos formation<br>(Miocene)                              | +   | Adjacent<br>Well 24  |
| 5...       | -             | 31                                     | Pacific Oil Co.           | Fresno | T. 20 S.,<br>R. 15 E. | 31           | .....               | .....         | Top water from above<br>3,000 ft.                             | -   | .....                |
| 6...       | +             | 48                                     | Pacific Oil Co.           | Fresno | T. 19 S.,<br>R. 15 E. | 11           | 1,650               | .....         | Vaqueros sandstone<br>(Miocene)                               | +   | .....                |
| 7...       | ++            | 36                                     | Pacific Oil Co.           | Fresno | T. 19 S.,<br>R. 15 E. | 11           | 2,850               | 37            | Vaqueros sandstone<br>(Miocene)                               | +   | .....                |
| 8...       | -             | 69                                     | Pacific Oil Co.           | Kern   | T. 31 S.,<br>R. 23 E. | 27           | 3,000               | .....         | Etchegoin   | -   | +<br>(1919)          |
| 9...       | -             | 4                                      | Pacific Oil Co.           | Kern   | T. 31 S.,<br>R. 23 E. | 35           | 3,280               | 24            | Etchegoin, Zone C?  | -   | +<br>(1922)          |
| 10...      | -             | 10                                     | Pacific Oil Co.           | Kern   | T. 31 S.,<br>R. 23 E. | 35           | 3,400               | 40            | Etchegoin, Zone C?  | -   | +<br>(1923)          |
| 11...      | -             | 114                                    | Pacific Oil Co.           | Kern   | T. 32 S.,<br>R. 23 E. | 1            | 2,977               | .....         | Etchegoin, Zone C?  | -   | Adjacent<br>Well 107 |
| 12...      | -             | 5                                      | Midland Oil Fields<br>Co. | Kern   | T. 31 S.,<br>R. 23 E. | 24           | About<br>4,300      | 23            | .....   | -   | .....                |
| 13...      | -             | 16                                     | Pacific Oil Co.           | Kern   | T. 32 S.,<br>R. 24 E. | 15           | 3,296               | .....         | Etchegoin, Zone B?  | -   | +<br>(1920)          |
| 14...      | -             | Schultz, No. 3                         | Standard Oil Co.          | Kern   | T. 32 S.,<br>R. 24 E. | 22           | 3,754               | .....         | Etchegoin, Zone C?<br>Edge well, SE. end<br>Buena Vista Hills | -   | .....                |
| 15...      | -             | 23                                     | Mascot Oil Co.            | Kern   | T. 32 S.,<br>R. 23 E. | 26           | 2,200               | .....         | Etchegoin   | -   | .....                |
| 16...      | -             | 13                                     | Mascot Oil Co.            | Kern   | T. 32 S.,<br>R. 23 E. | 26           | 2,600               | .....         | Etchegoin   | -   | .....                |
| 17...      | -             | 5                                      | Paraffin Oil Co.          | Kern   | T. 32 S.,<br>R. 23 E. | 25           | 1,548               | 45            | Etchegoin   | -   | .....                |
| 18...      | -             | 3                                      | Paraffin Oil Co.          | Kern   | T. 32 S.,<br>R. 23 E. | 25           | 1,530               | 43            | Etchegoin   | -   | .....                |
| 19...      | -             | 4                                      | Paraffin Oil Co.          | Kern   | T. 32 S.,<br>R. 23 E. | 25           | 1,612               | .....         | Etchegoin   | -   | .....                |
| 20...      | -             | Well 2, Kern<br>County,<br>lease No. 1 | Standard Oil Co.          | Kern   | T. 30 S.,<br>R. 25 E. | 31           | 3,261               | 41            | Edge water, NE. flank<br>Elk Hills, Upper<br>Etchegoin        | -   | .....                |
| 21...      | -             | 75                                     | Pacific Oil Co.           | Kern   | T. 12 S.,<br>R. 23 E. | 31           | 1,250               | .....         | Etchegoin, Zone B   | -   | Adjacent<br>Well 76  |
| 22...      | +             | 10                                     | Pacific Oil Co.           | Kern   | T. 12 S.,<br>R. 23 E. | 31           | 1,265               | .....         | Etchegoin, Zone B   | -   | +<br>(1920)          |
| 23...      | -             | 62                                     | Pacific Oil Co.           | Kern   | T. 11 S.,<br>R. 23 E. | 5            | 2,496               | .....         | Etchegoin, Zone B   | -   | +<br>(1919)          |
| 24...      | -             | 10                                     | Pacific Oil Co.           | Kern   | T. 12 S.,<br>R. 24 E. | 25           | 2,890               | 40            | Etchegoin, Zone B   | -   | +<br>(1920)          |
| 25...      | -             | Queen, No. 1                           | .....                     | Kern   | T. 11 S.,<br>R. 23 E. | 13           | 735                 | .....         | Etchegoin, Zone B   | +   | .....                |
| 26...      | -             | Diamond,<br>No. 2                      | .....                     | Kern   | T. 11 N.,<br>R. 23 W. | 13           | 750                 | .....         | Water from about 650<br>ft.                                   | ?   | +<br>(1915)          |
| 27...      | +             | Crown, No. 1                           | .....                     | Kern   | T. 11 N.,<br>R. 23 W. | 13           | 760                 | .....         | Etchegoin, Zone B   | +   | .....                |
| 28...      | -             | St. Paul, No. 1                        | .....                     | Kern   | T. 11 N.,<br>R. 23 W. | 13           | 700                 | .....         | Etchegoin, Zone B   | -   | .....                |
| 29...      | ++            | Conservative,<br>No. 4                 | Patterson and<br>Ballagh  | Kern   | T. 11 N.,<br>R. 24 W. | 12           | 870                 | .....         | Etchegoin, Zone B   | -   | .....                |
| 30...      | ++            | 10                                     | Northern Oil Co.          | Kern   | T. 11 N.,<br>R. 24 W. | 1            | 1,015               | 47            | Etchegoin, Zone B   | -   | .....                |
| 31...      | ++            | North Mon-<br>arch, No. 44             | Standard Oil Co.          | Kern   | T. 11 N.,<br>R. 24 W. | 2            | 2,380               | .....         | Maricopa shale  | -   | .....                |
| 32...      | ++            | Ida May,<br>water well                 | G. J. Hansen<br>property  | Kern   | T. 11 N.,<br>R. 24 W. | 2            | 2,500               | 47            | Water chiefly from<br>1,500 ft. in Mari-<br>copa              | +   | +<br>(1912)          |
| 33...      | +             | 37                                     | Ethel D. Oil Co.          | Kern   | T. 12 N.,<br>R. 24 W. | 36           | 2,135               | 44            | Maricopa shale  | -   | .....                |
| 34...      | ++            | 1-W                                    | Patterson and<br>Ballagh  | Kern   | T. 11 N.,<br>R. 24 W. | 13           | 2,500               | .....         | Flowing water well,<br>Maricopa shale                         | +   | .....                |
| 35...      | -             | 1                                      | Pliocene Oil Co.          | Kern   | T. 11 N.,<br>R. 23 W. | 18           | 900                 | 30            | Etchegoin   | -   | .....                |
| 36...      | +             | Monarch,<br>No. 34                     | Standard Oil Co.          | Kern   | T. 11 N.,<br>R. 24 W. | 2            | 1,590               | .....         | Etchegoin   | -   | .....                |
| 37...      | -             | Taft, water<br>supply                  | .....                     | Kern   | .....                 | .....        | 300                 | .....         | .....   | -   | .....                |

\* One plus sign indicates moderate, two signs, vigorous reduction. Minus sign signifies no reduction.

TABLE II—Continued  
CALIFORNIA OIL-FIELD WATERS

| Sample No. | Precipitate of FeS by Sulphate-reducing Bacteria; Medium 1.1 (No Salt) | Precipitate of FeS by Sulphate-reducing Bacteria; Medium 1.2 (3% NaCl) | Remarks   |
|------------|--|--|---|
| 1.....     | Negative   | 14th day, moderate; 21st day, abundant                                 | Constantly pumping, sample from 25 ft. lead line; negative to phenolphthalein   |
| 2.....     | 8th day, slight; 10th day, abundant                                    | Negative   | Constantly pumping; not salty to taste  |
| 3.....     | 6th day, moderate; 21st day, abundant                                  | 4th day, abundant  | About 600 ft. east of No. 2; not salty to taste   |
| 4.....     | 2d day, slight; 4th day, moderate; 21st day, abundant                  | 2d day, slight; 4th day, abundant                                      | Not salty to taste; with BaCl <sub>2</sub> only slight clouding, i.e., sulphates low  |
| 5.....     | Negative   | Negative   | BaCl <sub>2</sub> shows sulphates moderately abundant; leaky casing admitted top water; packing recently set                                  |
| 6.....     | Negative   | 1st day, slight; 21st day, slight                                      | Constantly pumping; strong odor of H <sub>2</sub> S; sample from 800 ft. lead line; not salty to taste  |
| 7.....     | Negative   | 1st day, slight; 3d day, moderate                                      | Strong odor of H <sub>2</sub> S; very slight precipitate with BaCl <sub>2</sub> ; negative to phenolphthalein                                 |
| 8.....     | Negative   | Negative   | Paint pink with phenolphthalein; salty taste; sample from gas trap 200 ft. from well  |
| 9.....     | Negative   | Negative   | Sample taken at bleeder at head of well; salty taste  |
| 10.....    | Negative   | Negative   | Sample from bleeder   |
| 11.....    | Negative   | Negative   | Sample from gas trap; no precipitate with BaCl <sub>2</sub> ; taste, salty  |
| 12.....    | Negative   | Negative   | Sample from bleeder; slight precipitate with BaCl <sub>2</sub>  |
| 13.....    | Negative   | Negative   | Sample from gas trap 200 ft. from well; taste, salty  |
| 14.....    | Negative   | Negative   | Sample from bleeder; negative to phenolphthalein and BaCl <sub>2</sub> ; taste, salty   |
| 15.....    | Negative   | Negative   | Taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>   |
| 16.....    | Negative   | Negative   | Taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>   |
| 17.....    | Negative   | Negative   | Sample from 140 ft. lead line; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>  |
| 18.....    | Negative   | Negative   | Sample from 500 ft. lead line; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>  |
| 19.....    | Negative   | Negative   | Sample from 130 ft. lead line; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>  |
| 20.....    | Negative   | Negative   | Sample from bleeder; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>  |
| 21.....    | Negative   | Negative   | Constantly pumping; sample from 500 ft. lead line; negative to phenolphthalein and BaCl <sub>2</sub> ; taste, salty                           |
| 22.....    | 21st day, moderate   | 8th day, moderate; 10th day, abundant                                  | Constantly pumping; sample from 100 ft. lead line; taste, salty   |
| 23.....    | Negative   | Negative   | Sample from gas trap 100 ft. from well; taste, salty  |
| 24.....    | Negative   | Negative   | Sample from 75 ft. lead line; taste, salty  |
| 25.....    | Negative   | Negative   | Constantly pumping; sample from 40 ft. lead line; negative to phenolphthalein and BaCl <sub>2</sub> ; taste, salty                            |
| 26.....    | Negative   | Negative   | Constantly pumping; mostly water  |
| 27.....    | 10th day, slight; 12th day, moderate                                   | 8th day, slight; 10th day, moderate; 21st day, abundant                | Sample from 150 ft. lead line; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>  |
| 28.....    | Negative   | Negative   | Negative to phenolphthalein and BaCl <sub>2</sub> ; taste, salty  |
| 29.....    | 2d day, moderate; 21st day, abundant                                   | 2d day, slight; 4th day, moderate; 21st day, abundant                  | Very viscous oil; sample from 20 ft. lead line; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>                               |
| 30.....    | 6th day, slight; 8th day, moderate; 21st day, abundant                 | 2d day, slight; 6th day, moderate; 8th day, abundant                   | Sample from 150 ft. lead line; negative to phenolphthalein and BaCl <sub>2</sub> ; taste, salty   |
| 31.....    | 6th day, abundant  | 6th day, moderate; 21st day, abundant                                  | Very heavy oil; sample from 100 ft. (lead line); taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>                              |
| 32.....    | 9th day, slight; 20th day, moderate                                    | 1st day, slight; 3d day, moderate; 20th day, abundant                  | Sample direct from head of flowing well; faint pink with phenolphthalein; negative to BaCl <sub>2</sub> ; taste, salty                        |
| 33.....    | 6th day, moderate; 8th day, abundant                                   | Negative   | Sample from 75 ft. lead line; new well, producing only 3 days; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>                |
| 34.....    | Negative   | 4th day, slight; 6th day, moderate; 8th day, abundant                  | Sample from 1 mile lead line; not salty to taste; constantly flowing for years; some precipitate with BaCl <sub>2</sub>                       |
| 35.....    | Negative   | Negative   | Sample from 40 ft. lead line; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub> ; oil very viscous                              |
| 36.....    | 6th day, slight; 8th day, abundant                                     | Negative   | Sample from 30 ft. lead line; taste, salty; negative to phenolphthalein and BaCl <sub>2</sub>   |
| 37.....    | Negative   | Negative   | Fresh water; negative to phenolphthalein; some precipitate with BaCl <sub>2</sub> ; from spigot few feet from head of constantly pumping well |

three carried  $H_2S$  in amounts recognizable by field tests. Of the twenty-one samples that carried no sulphate-reducing bacteria, only one carried  $H_2S$ .

Among the wells sampled sulphate-reducing bacteria were restricted to the southeastern part of the field in the general vicinity of the village of Maricopa, as is shown in Figure 7. The depths of these wells ranged from 760 to 2,500 feet. For these waters only two analyses are available; these are shown in Figure 8 (Nos. 22 and 32). Among the waters showing bacteria, No. 22, from a well near Kerto, was farthest from the southwest edge of the Sunset-Midway synclinorium and near the crest of Thirty-Five anticline. It is a brine almost free from sulphates, and belongs to the waters grouped as Class II on page 1284. It is a typical connate water close to normal sea water in concentration. Number 32 from near the southwestern edge of the synclinorium is an alkaline water of much lower concentration, and belongs to Class III as grouped on page 1284. From their location it is probable that most of the waters that yielded the bacteria belong to Class III. Oils from two of the wells yielding bacteria, Nos. 29 and 31, were the most viscous oils encountered in the sampling.

It is noteworthy that many wells in this district whose waters were low in sulphates failed to show sulphate-reducing bacteria. These include seven samples from the Buena Vista Hills, one sample from the Elk Hills, five samples from the Spellacy anticline, and two from near Thirty-Five anticline. The depths of these wells range from 1,250 to about 4,300 feet. Analyses are available for only five of these waters—8, 9, 10, 13, and 24. These five brines more closely resemble sea water in composition and concentration than do any other waters sampled in the district. Their most consistent difference from sea water lies in their small sulphate content, 0.12–0.29 in reacting value by percentage as contrasted with 4.6 for normal sea water. It is probable, therefore, that reduction of sulphates has taken place in these waters. Whether the reduction took place through bacterial action at the time of burial of the sediments as suggested by Murray's marine studies or through later bacterial action or through non-bacterial agencies remains for the present uncertain.

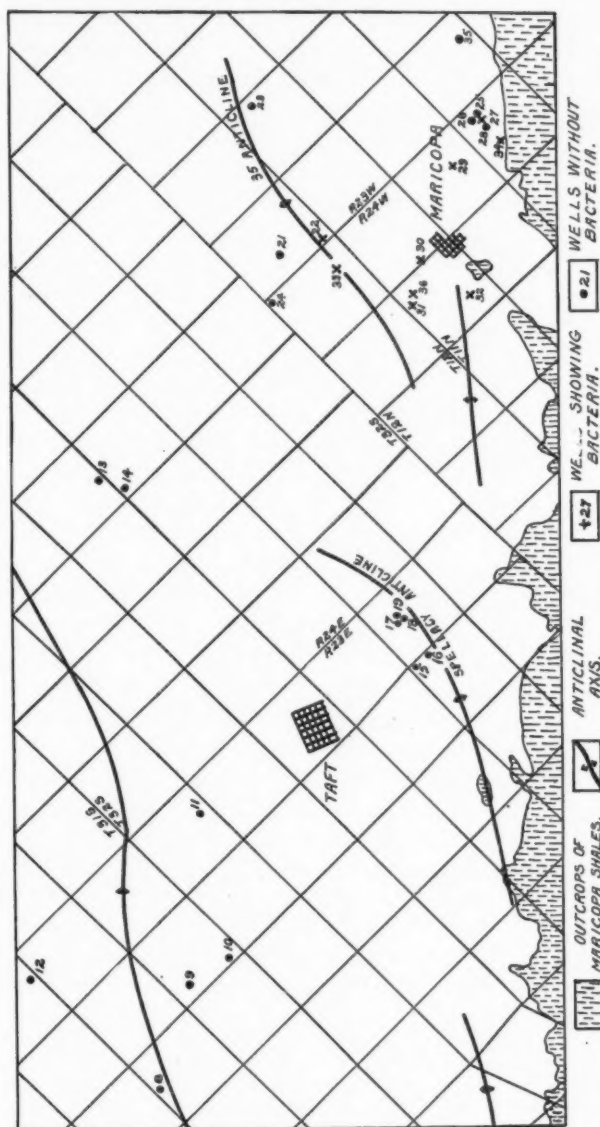


FIG. 7.—Map showing locations of wells in Sunset-Midway oil field, Calif., whose waters were tested for sulphate-reducing bacteria

One afternoon was spent in the Coalinga District,<sup>1</sup> Fresno County, where eight samples were collected. The district lies along the northeastern base of the Diablo Mountains. In the west side of the district oil occurs mainly in the Jacalitos formation of Miocene age in a monoclinal fold. Samples 1-5, inclusive, were from this side. In the east side of the field oil occurs mainly in the Vaqueros sand-

stone, also Miocene age, along the Coalinga anticline and along a monocline lying farther north. Samples 6 and 7 were from this monocline.

All of the six samples taken from wells producing oil in this field contained sulphate-reducing bacteria. They came from depths of 1,300 to 3,090 feet. Sample 5 from a well producing only top water showed no bacteria. For three of the bacteria-bearing waters all from the west side of the field (Nos. 1, 2, and 3), analyses are available from which

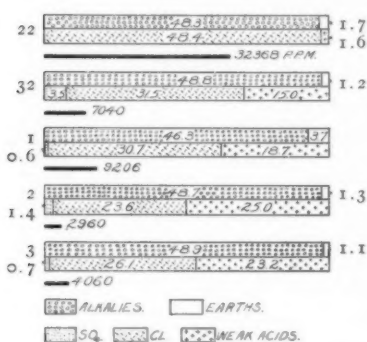


FIG. 8.—Graphs of waters from Sunset-Midway and Coalinga oil fields, Calif. Components plotted in terms of reacting values in percentage. Concentration in parts per million shown by heavy black lines.

the graphs shown in Figure 8 are plotted. All are alkaline waters very similar in composition to No. 32 from the Sunset-Midway field, which also carried bacteria. Three of the six carried appreciable amounts of  $H_2S$ .

In general for the two California fields studied, the waters carrying sulphate-reducing bacteria appear to be connate brines diluted and modified in composition through admixture with water from other sources. From these other, and presumably surface, sources came the supply of sulphates necessary to the life of sulphate-reducing bacteria, and from the oil came the organic matter equally necessary to their life. Whether the bacteria originated in the connate brines or were carried down in the waters descending from the sur-

<sup>1</sup> Ralph Arnold and Robert Anderson, "Geology and Oil Resources of the Coalinga District, California," *U.S. Geol. Survey Bull.* 398, 1910.

face is unknown, but the two samples of surface water obtainable were free from sulphate-reducing bacteria.

Many of the California wells samples are characterized by higher temperatures than any observed in the Illinois fields, temperatures ranging from 40° to 47° C. being not uncommon. The cultures obtained from the California waters are identical in general appearance with those obtained from the Illinois waters but develop more rapidly, notable growths being obtained in some cases overnight. Pure cultures of the California bacterium have not yet been prepared. It is possible that the organism is thermophilic and related to *Vibrio thermodesulfuricans* of Elion.

November, 1926

## GEOLOGICAL NOTES

### PHANTOGRAPH MODEL

The phantograph model is an improved method of portraying geological data in three dimensions. The method makes use of the peg or rod, as in the well-known peg models, but used in such a way as to produce results which are impossible under the old system of making peg models.

The device consists of a plat board upon which all geological data are mounted, the rods which support the data in space, and the rod holders which attach the rods to their proper position on the plat board.

The plat board is a soft pine board 6 feet square and  $1\frac{1}{4}$  inches thick, and constructed so as to maintain a flat surface free from warp. The board is painted white, and ruled off to represent a township subdivided to 40-acre tracts. When used in unsectionized areas the board is covered with paper, and upon this paper is laid out the map work on a scale of one foot to the mile. The rods are of aluminum,  $\frac{1}{8}$  inch in diameter, upon which are mounted pieces of cork  $\frac{1}{2}$  inch in diameter, spaced along the rods according to the requirements of the data. The corks are painted to represent the following features: blue represents lime; orange represents sand; black represents production; black crosses on orange indicate gas; red is the symbol for water; and green is used for shale, sandy shale, or broken sand. The rod holders consist of a tube with a screw or pin at one end. In use the rod holders are screwed or driven into the board at the proper place, and are removable. When the rod is placed in the tube of the holder, the rod is held in its proper place and position.

Visibility, the primary objective in model construction, is obtained by a combination of mechanical features and color selections. Mounting corks of  $\frac{1}{2}$ -inch diameter on rods of but  $\frac{1}{8}$ -inch diameter accentuates the important data and at the same time eliminates congestion and obstruction of view resulting from the use of full-diameter rods or pegs. The use of a big cork and a small rod produces a "stereogram effect," while at the same time the individuality of each well is preserved. The orange color for sands and the blue color for limes are easily recognized, but sufficiently

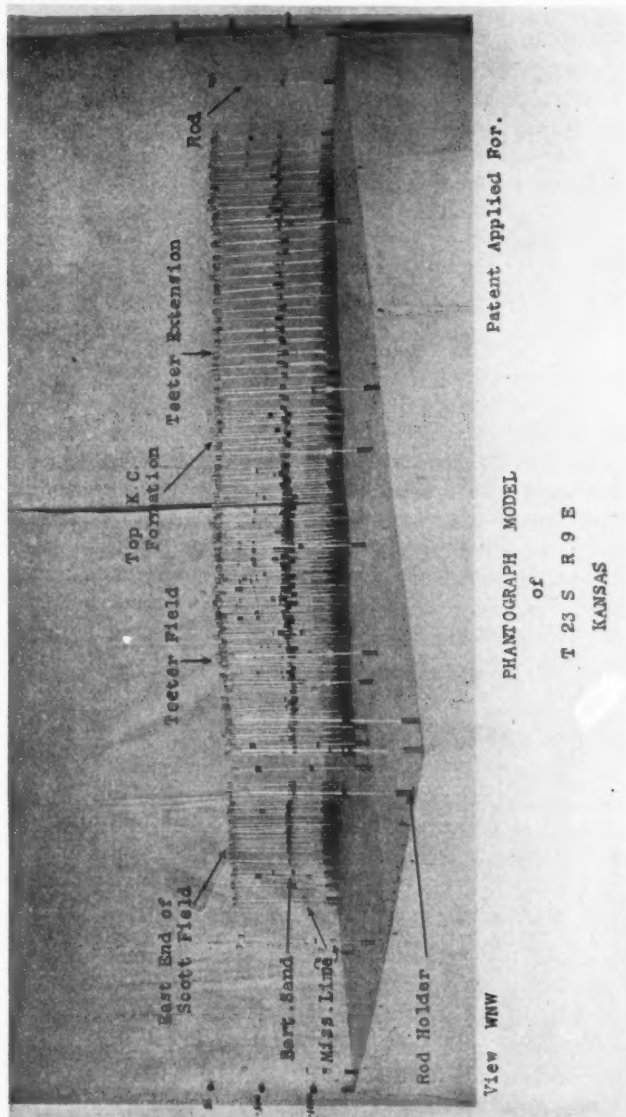


FIG. 1.—On account of photographic limitations, the zones of dry sand, gas, oil, and water do not show separately. On account of their colors they photograph as a solid black.

soft in tone so as not to clash with the solid black for production and the red for water. These colors mounted on a white rod add to the desired effect. Visibility is further aided by eliminating all unimportant data and showing only the essential features. For example, the photograph shows a zone from the top of the Kansas City formation to, and including, the top of the "Mississippi lime," together with all sands in that zone. The sands are colored to conform to their content—be it oil, gas, water, or dry.

The feature of having the rods detachable from the rod holders permits a more flexible use of the model material than is possible in the old-form models. When the study of an area under observation is completed, the rods are removed from the rod holders and the rod holders are removed from the board, thus clearing the board for use in another area. The rods from the dismantled model are filed away for future use. In filing the rods, the unit of area used is the township, and all records involved are indexed to that unit. Each rod is given a township well number which corresponds to the geological record card of the same number. The township well numbers range from one up to as many wells as there are in the township, and the geological record card gives all the important information about the well. As an example, we have a rod marked -14.K.23.9.59. This means that the subsea datum for the township is 1,400 feet below sea-level; the township is in Kansas, indicated by the letter K; the township is T. 23, R. 9. (south and east unless otherwise indicated); and the township well number is 59. Referring to the geological record card of the same number we find a record of Greenland—Green No. 10, located in the southeast corner of the northeast quarter of Section 10, Township 23, Range 9, elevation 1,436, drilled to a total depth of 2,375 feet; the Oswego group (driller's) is 1,689 to 1,880 (-253, -444); sand, 2,314 to 2,319 (-878, -883); gas, sand, 2,319 to 2,329 (-883, -893); sand, 2,329 to 2,340 (-893, -904); gas, sand, 2,340 to 2,375 (-904, -936); oil; the well is a producer; and there is a written log in the files. By numbering and indexing the rods the model material can be used for studying a general assembly, cross-sections, or a particular lease or area in the township.

The phantomograph model is simple and requires no expert knowledge or skill in construction. The materials used are cheap and easily handled, and the rods take but little time in their construction. The model enables the operator to see the story at a glance; the geologist can tell his story in a simple and forceful manner; he can study the comparative geology of multiple horizons; he can pick out errors in his data; he can reduce the personal equation in contouring to the minimum; he can

watch the "edge problem," which shows up in all fields sooner or later. The model is very well adapted for use in connection with the ultimate recovery of oil, such as flooding the sands with gas, air, or water.

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### UNCONFORMITIES IN THE PENNSYLVANIAN

In a recent interesting article Moore<sup>1</sup> deduces, from evidence obtained west of the Nemaha granite ridge in central Kansas, a period of uplift and erosion during the Pennsylvanian. Although unable, from this evidence, to set the exact time of this erosion, he inclines to a date late in Cherokee time, suggesting a possible correlation with the "shoestring sands" of eastern Kansas, so ably described by Rich,<sup>2</sup> as formed very near the close of the Cherokee. In western Missouri and extending northeast into south-central Iowa, however, there are widespread evidences of a period of uplift and erosion at a slightly later time, near the close of the Pleasanton epoch (late in the Marmaton of Kansas).

The most striking proof of this erosion is furnished by the Warrensburg and Moberly channels,<sup>3</sup> the former passing through Warrensburg and near Lexington, Missouri, and the latter through Moberly. These channels were remarkably long, narrow, and straight, and cut into and removed at least 200 feet of earlier Pennsylvanian beds that were already well consolidated, including the upper part of the Cherokee, all the Henrietta (lower "Marmaton"), and the lower part of the Pleasanton. They were steep-sided, averaged 2 to 3 miles in width, and had few tributaries, resembling those made by fairly large streams like Red River of the North, where it flows through very youthful plains. Where now exposed, the Warrensburg channel can be traced 50 miles, and the Moberly, 40 miles, and their original lengths were undoubtedly much greater. The Warrensburg river probably flowed from south to north off the Ozark uplift, and the Moberly, from east to west off a north-

<sup>1</sup> Raymond C. Moore, "Early Pennsylvanian Deposits West of the Nemaha Granite Ridge, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 205-16.

<sup>2</sup> John L. Rich, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 103-13; and Vol. 10 (1926), pp. 568-80.

<sup>3</sup> Henry Hinds and F. C. Greene, "Stratigraphy of the Pennsylvanian of Missouri," *Missouri Geol. Survey*, Vol. 13 (1915), pp. 90-106.

eastern tongue of that uplift, perhaps joining the Warrensburg near Lexington by way of the present Missouri River Valley. A short time before the deposition of the Kansas City formation, both channels were filled with sands and muds, a little peat, and conglomerate containing fragments of Fort Scott limestone. Plant fossils from near the coal lenses have been identified as Pennsylvanian.

Other evidences of an unconformity in the Pleasanton (upper "Marmaton") are numerous in north Missouri and south-central Iowa, especially sandstones that cut down and into older Pennsylvanian deposits and have in places conglomerates at their bases. The amount of evidence that has been obtained is surprising, considering the relatively unimportant economic status of the formation and the fact that so much of its outcrop is covered by glacial drift. It is noteworthy that emergence from the sea, sub-aerial erosion, and subsequent submergence of the formation took place with little folding, since Kansas City limestones are essentially parallel with the Fort Scott and associated beds.

Another period of erosive activity that is probably not so significant is in evidence in the Douglas formation near Leavenworth,<sup>1</sup> where more than 100 feet of the normal succession beneath the Oread limestone are replaced by sandstone that has an uneven base and carries in places a basal conglomerate of brecciated limestone. It might be expected that local unconformities such as this would be plentiful throughout the Pennsylvanian of Missouri and Iowa, characterized as it is by alternations of terrestrial coals and closely associated marine limestones. The surprising thing, however, is that these are not particularly plentiful except in the Pleasanton and the basal Cherokee, and that both the limestones and the coals retain their individual peculiarities over a remarkably large territory. Evidently changes in the relative level of sea and land were commonly effected without folding and without disturbing the uniform conditions that had formerly prevailed over wide areas. The development of a drainage system like that of the Warrensburg and Moberly channels is, therefore, all the more notable. It would be interesting to learn whether it can be correlated with possibly contemporaneous erosion in Kansas and Oklahoma.

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ROOM 421  
250 PARK AVENUE  
NEW YORK CITY

<sup>1</sup> Henry Hinds and F. C. Greene, "The Leavenworth and Smithville Quadrangles, Kansas-Missouri," *U. S. Geol. Survey Folio 206* (1917), p. 6.

## BAROMETRIC LEVELING

Barometric leveling is exceedingly simple, but accurate results can be obtained only by observing and correcting for certain sources of error. The error introduced by changes in meteorologic conditions is universally recognized and largely eliminated by adjustments of barometric readings.<sup>1</sup> Errors due to the difference in accuracy of the two classes of barometric formulas—static and dynamic—developed to lay out the altitude scale, are so far within the customary limits of permissible error that they are not treated. The third source of error, due to temperature of the air-column, is not commonly recognized. Surveying aneroid barometers are labeled "Compensated." While this implies compensated for temperature changes, it applies only to errors due to expansion or contraction of the metal parts of the instrument with temperature variation. The altitude scale is based upon Ferrels' formula,<sup>2</sup> in which the mean temperature is assumed as 50° F. whereas in practice the atmospheric temperature may range from as much as 50° or more above to 50° or more below the assumed mean. Since this temperature correction for altitude scales is as much as 10 feet in every 100 feet of altitude at 100° F., or 0° F., a further correction should be applied as follows:<sup>3</sup>

Add 2 per cent in each 100 feet of altitude for each 10 degrees F. above 50° F. Subtract 2 per cent each 100 feet of altitude for each 10 degrees F. below 50° F.

HENRY A. LEY

TULSA, OKLAHOMA  
October 16, 1926

## GEOPHYSICS AT COLORADO SCHOOL OF MINES

The world's first department of geophysics is being established at the Colorado School of Mines, thanks to the alertness of John M. Wilson, of the Pan American, the vision of President Coolbaugh, and the co-operation of a number of oil companies. Dr. C. A. Heiland, well known to oil geologists interested in geophysical work, will be head of the department. The intention is to carry on research work in the application of geophysical methods to the development of mineral deposits, to train men for practical geophysical work in the oil and mining industries, and to

<sup>1</sup> F. H. Lahee, *Field Geology* (New York: McGraw-Hill, 1923), 2d ed., pp. 430-44.

<sup>2</sup> U. S. Coast and Geodetic Survey Report, 1881, Appendix 10.

<sup>3</sup> Smithsonian Miscellaneous Collection No. 21; F. H. Lahee et al., *Instruments in Geologic Field Mapping*, Rochester, New York: Taylor Instrument Companies (1926), p. 21.

inspire picked men to carry on further research work both in industry and in educational institutions. Courses basic to geophysical work are now being offered in the geology department under Professor Van Tuyl, in the physics department under Professor Bellis, and in the mathematics department under Professor Risley. Beginning with the next semester, Dr. Heiland will offer a series of courses in geophysical principles and geophysical methods. It is planned to give broad foundation courses to undergraduate students, with advanced specialized work available for graduate students, especially for men who have already had some experience in geologic work.

More than one thousand men are today employed by oil companies on torsion balance, seismograph, and magnetometer work in the United States alone. In the nature of things, most of these men have had incomplete training in the principles of the work they are doing. President Coolbaugh and Dr. Heiland feel that a real service can be rendered the industry by educating men in geophysical principles, giving them preliminary training in geophysical methods, and above all developing the research spirit in the application of these methods to the problems at hand.

MAX W. BALL

DENVER, COLORADO

October, 1926

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### OKLAHOMA SURVEY, SEVENTH FIELD CONFERENCE

#### OUACHITA MOUNTAINS OF OKLAHOMA

The seventh field conference under the auspices of the Oklahoma Geological Survey was held in the Ouachita Mountain region the week beginning October 11, 1926. The following geologists were present:

|                                   |                                     |
|-----------------------------------|-------------------------------------|
| W. T. Thom, Jr., Washington, D.C. | C. W. Honess, Bartlesville, Okla.   |
| David Donoghue, Fort Worth, Tex.  | J. B. Kennedy, Oklahoma City, Okla. |
| L. P. Teas, Shreveport, La.       | Hubert Bales, Oklahoma City, Okla.  |
| W. C. Spooner, Shreveport, La.    | John Fitts, Ada, Okla.              |
| Darwin Benedum, San Antonio, Tex. | A. J. Williams, Norman, Okla.       |
| C. W. Tomlinson, Ardmore, Okla.   | F. A. Melton, Norman, Okla.         |
| R. A. Birk, Ardmore, Okla.        | C. L. Cooper, Norman, Okla.         |
| George E. Burton, Ardmore, Okla.  | John S. Redfield, Norman, Okla.     |
| Sidney Powers, Tulsa, Okla.       | Chas. N. Gould, Norman, Okla.       |
| R. J. Riggs, Bartlesville, Okla.  |                                     |

The party left Hugo Monday morning, October 11, drove east through Idabel to Broken Bow, thence northwest over the outcrops of the lower Paleozoic formations to Bethel. The rocks studied were the Womble, Polk Creek, Big Fork, Arkansas novaculite, and the base of the Stanley shale. The most interesting things noticed on the day's trip were the great amounts of intrusive quartz in the region and the very conspicuous tuff bed near the base of the Stanley shale. The trip included a visit to the edge of the game reserve on Mountain Fork Creek. That night a banquet was served by the chamber of commerce at Broken Bow, which was very much appreciated by the geologists.

Tuesday morning the party drove from Broken Bow to Glover Creek and studies were made of the Collier shale and the Crystal Mountain sandstone, these being the oldest formations exposed in this part of Oklahoma. Rain interfered with the work in the afternoon, and the party visited the immense lumber mills of the Choctaw Lumber Company at Broken Bow. Late in the afternoon they drove to Idabel, studying a section of the Cretaceous on the way. The Lions Club at Idabel tendered a banquet to the visiting geologists.

Wednesday the party drove west from Idabel to Valliant, where a visit was made to an asphalt quarry in the upper part of the Trinity sand. Thence to old Fort Towson, where we examined the buildings constructed of Goodland limestone almost 100 years ago. The party drove south from Hugo across Red River, studying the deposits of the Bennington limestone and Woodbine sandstone on the way. After lunch at Hugo they went north toward Antlers, studying the Washita-Goodland and Trinity division of the Comanche-Cretaceous. From Antlers the party drove east beyond Rattan, studying the Trinity, Jackfork, and Stanley, and back to Antlers for the night.

Thursday the party drove north from Antlers over Kiamichi Mountain, where a fine highway is being constructed, to Clayton, thence north to Sardis to study a famous asphalt deposit which is not now being worked. From Sardis they drove east through Tuskahoma to Albion, and visited Round Prairie among the Potato Hills northwest of that place. The rocks in the Round Prairie are the Stringtown shales, overlain by the Talihina chert, which formation makes up the great part of the Potato Hills. These hills as a whole constitute a dome, forming the core of this part of the Ouachita Mountains. The party went to Talihina for the night.

Friday, leaving Talihina, they visited a deposit of coal several miles to the east, thence to the Choctaw-Chickasha Sanitorium and the

Oklahoma Tubercular Sanatorium west of Talihina. Thence over the very fine highway across Winding Stair Mountain to Wister, through Howe and Heavener, studying on the way the Jackfork sandstone, the Atoka, and the Hartshorne formations. The night was spent at Poteau.

Saturday morning the party left Poteau, traveled westward along the strike of the McAlester shales to Wilburton, crossing the Hartshorne sandstone on to the Atoka formation; then west across the McAlester anticline and Krebs syncline to Hartshorne, where studies were made of the Wapanucka limestone and Caney shale; thence to McAlester for lunch. In the afternoon they drove west through Stuart, Calvin, Allen, to Ada, working down the dip of the various Pennsylvanian formations from the McAlester shales to the rocks of Pontotoc County; thence back to Norman by way of Stratford, Paoli, and Purcell.

Taking it all in all, this was in many ways the most successful field conference which has as yet been held. The crowd was congenial, and in spite of rainy weather with the attendant discomforts, everyone had an enjoyable and profitable time.

CHAS. N. GOULD, *Director*

OKLAHOMA GEOLOGICAL SURVEY  
NORMAN, OKLAHOMA  
November 2, 1926

## REVIEWS AND NEW PUBLICATIONS

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*Petroleum Development and Technology in 1925.* BY MANY AUTHORS, CONTAINING PAPERS PRESENTED AT SYMPOSIUM OF PETROLEUM DIVISION AT THE NEW YORK MEETING, FEBRUARY 15 TO 17, 1926, THE LOS ANGELES JOINT SESSION, JANUARY 21, 1926, AND THE CASPER, WYOMING, MEETING AUGUST 28 TO 30, 1926. New York: American Institute of Mining and Metallurgical Engineers, Inc., 1926. Pp. 784; figs., 197.

Petroleum development has moved forward at an unprecedented rate during the past decade, especially in the United States, Mexico, and South America. A measure of the rate of this development is afforded in figures recently issued, showing the large proportion of the world's total production which has been made during the past five years. This enormous draft on the country's petroleum resources, brought about by the ever increasing demand for petroleum products and the fear of their ultimate exhaustion, has created a feeling for the need of greater economy and efficiency in the production of oil, thus stimulating development in petroleum technology. Never in the history of the industry has petroleum technology been advanced so rapidly as during the past five years. The authors in this book not only review progress in 1925, but record, perhaps for the first time, discoveries made and processes and methods perfected by petroleum chemists and technologists in other branches of the subject, which are far-reaching in their significance.

The contributions in this volume have been arranged in five parts. In Part I is set forth the results obtained by the Petroleum Division of the Institute in assembling the information in its present form, and also a brief review is given of the scope of the subject matter treated in the volume.

Part II, entitled "Production Engineering," contains a number of excellent papers on this ever developing branch of petroleum engineering by men in actual contact with this important phase of the industry. The service which technology is rendering to the production of oil is well illustrated by these papers. Prominent among the contributions are papers dealing with improved methods of core drilling, greater recovery of oil by gas lift, flooding, more efficient pumping, and mining. Methods of deep-well pumping and cleaning by compressed air are also treated.

Various contributions by recognized authorities in the field of petroleum chemistry are included in Part III under the caption of "Refining Technology." These papers illustrate the unprecedented progress which has been made in the past few years in the cracking of petroleum and the influence this development

will have on the future of the industry. The large percentage of gasoline output of the United States which is already being produced by cracking processes and the very great increase in the percentage of gasoline which it is claimed will be made by cracking processes in the near future is worthy of note. The percentage of gasoline that can be made through cracking processes of any grade of crude, 50 per cent or more, is a further index of the progress that is being made along these lines. An interesting feature of this chapter is found in the detailed descriptions of the different cracking processes now in use, together with their special advantages as pointed out by their inventors.

In the chapter (Part IV) on "Transportation Engineering," some interesting papers are presented which have a very practical bearing on the movement of oil. This branch of the industry has perhaps not experienced as rapid development as other lines, yet there are some interesting papers on evaporation in transportation and storage, also losses due to breakage in crude oil pipe-lines.

Under the heading of "Production," Part V, the usual review of world-production by authors familiar with the development taking place in the different oil-producing countries is given. This material is arranged in easily available form and the information concerning foreign countries is more elaborate than has been published in previous years by the Institute.

Part VI, dealing with "Petroleum Economics," contains a number of very interesting and instructive papers on the economics of the petroleum situations by men who may be regarded as authorities on this subject.

The volume brings together a large amount of excellent, up-to-date information on all phases of petroleum technology, as well as a very interesting review of progress made during 1925. It is believed that the Petroleum Division of the A. I. M. E. has rendered a real service to the industry in assembling and presenting in condensed form this authentic treatise on *Petroleum Development and Technology in 1925*.

C. A. FISHER

DENVER, COLORADO  
September 29, 1926

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"Oil-Bearing Formations of Southwestern Arkansas." *U. S. Geological Survey Press Bulletin 8823*, September 10, 1926. 7 mimeographed pages; 1 diagram of stratigraphic relations.

The Department of the Interior, through the Geological Survey, with the advice and co-operation of George C. Branner, state geologist of Arkansas, has just completed a geologic investigation yielding results that will be of practical interest to all geologists engaged in the search for oil and gas fields in southern Arkansas and northern Louisiana. In these regions the finding of hidden structure favorable to the occurrence of oil and gas has been hampered by the scarcity of information as to the variations in thickness and character of the buried Cretaceous formations, and uncertainties arising from this cause have added greatly to the aggregate cost of wildcat exploration. This article presents a condensed description of the Cretaceous formations which reach the surface

in southwestern Arkansas, north of Red River and east of the Oklahoma line. It thus affords a guide to the interpretation of the logs of exploratory wells drilled in areas in southern Arkansas and northern Louisiana where these formations are under cover, and hence where they may contain oil and gas in commercial quantities if local structural conditions are favorable. "The field work on which this article is based consisted of a study of the Upper Cretaceous outcrops in southwestern Arkansas, supplementing work previously done by H. D. Miser. The investigation was carried out by C. H. Dane, with the advice and under the general guidance of L. W. Stephenson and with the assistance of P. D. Torrey.

#### OKLAHOMA GEOLOGICAL SURVEY

Progress of the work of the Oklahoma Geological Survey during the past year is indicated by the list given herewith.

In 1925 the Survey issued the following publications:

Bulletin 4, Coal in Oklahoma, by C. W. Shannon, *et al.*, revised by C. L. Cooper.

Bulletin 31, Identification of Heavy Minerals, by Edson.

Bulletin 33, Geology of Love County, by Bullard.

Bulletin 34, Geology of Cimarron County, by Rothrock.

Bulletin 35, Index to the Stratigraphy of Oklahoma, by Gould.

During 1926 the following publications have come from the press:

Bulletin 36, Report on the Papoose Oil Field, by Bunn.

Bulletin 37, Geology of Texas County, by Gould and Lonsdale.

Bulletin 38, Geology of Beaver County, by Gould and Lonsdale.

Bulletin 39, Geology of Marshall County, by Bullard.

Bulletin 40, Oil and Gas in Oklahoma. This bulletin is being published as separates, of which the following have been issued:

Bulletin 40-A, Geology of Alfalfa, Woods, Harper, Ellis, Woodward, and Major counties, by Clifton.

Bulletin 40-B, Subsurface of Northeastern Oklahoma, by White.

Bulletin 40-C, Geology of Creek County, by Merritt and McDonald.

Bulletin 40-D, Subsurface of Northwestern Oklahoma, by Greene.

Bulletin 40-E, Oil and Gas in Stephens County, by Frank Gouin.

Other chapters of Bulletin 40 have been promised during the next few weeks, and they will be printed as the manuscripts are received. Oklahoma geologists who have promised these chapters and who are now working on them are: E. G. Woodruff, Ed Bloesch, R. H. Wood, J. R. Bunn, Philip Boyle, F. C. Greene, C. W. Tomlinson, G. C. Clark, R. W. Clark, L. E. Kennedy, Clyde Becker, R. A. Conkling, and Irving Perrine. We have not yet been able to secure anyone to write Osage, Washington, and Lincoln counties.

The following is the status of other publications:

Circular 9, Sycamore Limestone, by Cooper, ready for printing.

Circular 13, The Permian of Western Oklahoma and the Panhandle of Texas, by Gould and Lewis, ready for printing.

Circular 14, The Anadarko Basin, by Gould and Clifton, being written.

Bulletin 41, The Upper Paleozoic Rocks of Oklahoma, by Gould and Wilson, ready for printing.

Bulletin 42, Oklahoma's Mineral Resources, by Redfield, being written.

Bulletin 43, Underground Methods and Equipment for Producing Oil in Oklahoma, by H. C. George, being written.

Bulletin 44, Geology of Craig County, by Ohern, being revised.

Bulletin 45, Geology of Nowata County, by Ohern, being revised.

Bulletin 46, Geology of Washington County, by Ohern, being revised.

New Oil and Gas Map of Oklahoma, showing 287 fields, ready for distribution.

Geological map of Oklahoma, by Miser, final proof corrected. Should be available at the U. S. Geological Survey, Washington, D. C.

CHAS. N. GOULD, *Director*

NORMAN, OKLAHOMA  
September 16, 1926

## THE ASSOCIATION ROUND TABLE

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### MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following applicants for membership in the Association. This does not constitute an election, but places the names before the membership at large. In case any member has information bearing on the qualifications of these applicants, please send it promptly to J. P. D. Hull, Business Manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each applicant.)

#### FOR FULL MEMBERSHIP

Ralph C. Brehm, Denver, Colo.  
F. B. Plummer, Charles M. Rath, Max W. Ball  
Roderick D. Burnham, Los Angeles, Calif.  
Desaix B. Myers, Hoyt S. Gale, Frank S. Hudson  
Campbell M. Hunter, London, England  
Carroll H. Wegemann, William B. Heroy, Sidney Powers  
Eugene C. Templeton, Los Angeles, Calif.  
Desaix B. Myers, Hoyt S. Gale, Frank S. Hudson

#### FOR ASSOCIATE MEMBERSHIP

Leo N. Densmore, Okmulgee, Okla.  
David M. Logan, S. H. Andrews, S. W. Wells  
Kenneth S. Ferguson, Amarillo, Tex.  
C. Max Bauer, D. E. Lounsbery, Charles M. Rath  
James W. Kisling, Jr., Tulsa, Okla.  
Dollie Radler, Sidney Powers, C. R. Thomas  
Joseph J. Maucini, Amarillo, Tex.  
J. V. Howell, Rogers Van Gilder, C. Max Bauer  
James F. Pepper, Amarillo, Tex.  
F. W. Bartlett, M. E. Roberts, C. Don Hughes  
William E. Shamblyn, Tulsa, Okla.  
R. M. Gawthorp, Ray V. Hennen, Thomas W. Leach  
Silas F. Shaw, San Antonio, Tex.  
James F. Kemp, John R. Suman, R. B. Roark  
Clare J. Stafford, Tulsa, Okla.  
T. E. Weirich, Virgil O. Wood, Harry F. Wright

J. Basil Wagner, Chandler, Okla.

Sidney Powers, C. R. Thomas, Dollie Radler

Garnett A. Williams, Tulsa, Okla.

Richard Hughes, H. W. Peabody, R. S. McFarland

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FOR TRANSFER TO FULL MEMBERSHIP

Earl B. Noble, Los Angeles, Calif.

Desaix B. Myers, Frank S. Hudson, E. F. Davis

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VOLUME I

Copies of Volume I (1917) of the *Bulletin* of the Association (Southwestern Association of Petroleum Geologists) are no longer available at headquarters, the supply on hand having been exhausted except for the office copies. As headquarters receives frequent orders for the complete set of the *Bulletin*, it offers, as a service to members and subscribers, to pay the list price of \$5.00 each for copies of Volume I in good condition with covers. Address the Business Manager, Box 1852, Tulsa, Oklahoma.

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ASSOCIATION LIBRARY

Fred H. Kay, assistant to the president of the Pan-American Exploration Company, 120 Broadway, New York City, recently made a gift to the Association of 565 volumes and pamphlets from his geological library. This collection, which contains several important government publications long since unavailable from the usual sources, is now on the shelves at headquarters. The Association appreciates Mr. Kay's gift. Gifts of single volumes have been received from several sources. The official library now contains 600 volumes.

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ANNUAL MEMBERSHIP DUES

The annual dues in the Association for 1927, amounting to \$15.00 for full membership and \$8.00 for associate membership, become payable January 1. The Association depends primarily on receipt of these dues to pay for publishing the *Bulletin* and carrying on its business. Members, if you want your Association to function efficiently, pay your dues at once.

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GEOLOGICAL SOCIETY OF AMERICA

The Geological Society of America, the Paleontological Society, the Mineralogical Society of America, and the Society of Economic Geologists are all to hold their annual meetings in Madison, Wisconsin, December 27-29

inclusive. The Council of the Geological Society has sent a special invitation to the American Association of Petroleum Geologists to attend this meeting, as announced in the *May Bulletin*. This Association and the Society of Economic Geologists are planning a joint meeting at which the Association will be represented in part by E. L. DeGolyer with a paper on the application of geophysical methods to the finding of salt domes. All the meetings will be open to non-members of the societies, and some papers of special interest to oil geologists are expected. The Department of Geology and the Geological Survey of Wisconsin have extended a special invitation to members of the Association, and request of those planning to attend that they write W. H. Twenhofel, chairman of local committee of arrangements, University of Wisconsin, Madison, Wisconsin. Probable cost of the trip would include fare and a half for railroad trip and \$6.00-\$9.00 for room and board at the new University dormitories, or \$10.00-\$15.00 for hotel accommodations during the stay at Madison.

## AT HOME AND ABROAD

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### CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

JOHN F. WEINZIERL, chief geologist of the North American Exploration Company, Inc., Houston, Texas, gave a lecture on geophysical instruments and their application to prospecting for ore deposits and ore structures before the senior petroleum and geological students at the Colorado School of Mines, Golden, Colorado, last September.

A. C. HEILAND, of the American office of Askania Werke, 805 Keystone Building, Houston, Texas, has been secured by the Colorado School of Mines as professor and head of the newly established department of geophysics. The new course thus introduced embraces the use of the torsion balance, seismograph, magnetomic and electrical methods for scientific prospecting of oil and other mineral deposits.

EDWARD L. ROARK, who has been geologist for the Marland Refining Company for the past seven years, has moved from Ponca City to take a position as chief geologist with Jarvis and Holm in the Kennedy Building, Tulsa.

FRED B. TOUGH, production superintendent for Humphreys Corporation, Houston, Texas, lost his life October 24 in a fire in the oil field at Sour Lake, Texas. Previous to his connection with the Humphreys Corporation, Mr. Tough was chief petroleum engineer with the U. S. Bureau of Mines, Washington, D.C., and had long been active in oil field work and in engineering and geological societies concerned with petroleum geology. A later number of the *Bulletin* will contain a biography of his life.

E. DEGOLYER, president of the Amerada Petroleum Corporation, 65 Broadway, New York, spent several days in Tulsa the last part of October.

FRED H. KAY, assistant to the president of the Pan-American Exploration Company, 120 Broadway, New York City, was in Tulsa, Oklahoma, recently on business.

SHIRLEY L. MASON, of Huntley and Huntley, Frick building, Pittsburgh, Pennsylvania, has recently been engaged in field investigations in Texas.

WARNER W. NEWBY, geologist with the Roxana Petroleum Corporation at Tulsa, Oklahoma, lost his life October 25, 1926, when he lost control of his automobile while driving from Tulsa to Ponca City. A biography of Mr. Newby's life will be printed in a coming number of the *Bulletin*.

LEWIS B. KELLUM, Apartado 657, Tampico, Mexico, spent his vacation in the United States the past October and November.

EDWIN T. HODGE, professor of economic geology in the University of Oregon, at Eugene, has written an unusually well illustrated report on "Mount Multnomah, Ancient Ancestor of the Three Sisters." The book is published by the University of Oregon Press.

ROBERT H. DOTT, who has been working several years for the Carter Oil Company in southern Oklahoma, is now connected with the Mid-Continent Oil and Gas Company.

JOHN E. MILLAR, JR., formerly in the subsurface department of the Mid-Continent Oil and Gas Company, has resigned to go with the Prairie Oil and Gas Company.

ED GEORGE, who has been doing geological work in the Okmulgee district for the Amerada Petroleum Corporation the past five years, has resigned to go with the Independent Oil and Gas Company at Okmulgee.

W. G. BLANCHARD is working in southeastern New Mexico for the Marland Oil Company of Colorado.

EARL COLTON is consulting geologist at Okmulgee.

F. S. PROUT is in charge of the geological work for the Empire Gas & Fuel Company in the Artesia district of New Mexico.

E. W. BRUCKS, of the Transcontinental Petroleum Company of Mexico, spent October re-examining the structure of the Luling oil field.

V. H. McNUTT, for many years a consulting geologist at Tulsa, has moved to San Antonio, Texas. He retains his office at 216 Castle Building, Tulsa. He also has an office in Carlsbad, New Mexico. Mr. McNutt made the location for the discovery well in the Maljamar field, Lea County, New Mexico, east of the Artesia field.

RAE PREECE, of the Douglas Oil Company, has been transferred from Tulsa to San Antonio, Texas.

W. R. LONGMIRE, of the Gypsy Oil Company, is working in California on a temporary assignment.

KENNETH AID is consulting geologist at Cisco, Texas.

J. M. ARMSTRONG is in charge of the geological work of the Prairie Oil & Gas Company in Texas.

MISS GLADYS HAWLEY is now with the Silurian Oil Company, Tulsa, Oklahoma. Miss Hawley was formerly connected with the Illinois Geological Survey.

C. O. NICKELL, formerly division geologist for the Texas Company at Wichita Falls, is now with the Texhoma Oil Company at that city.

WILLIAM D. BLACKBURN is in charge of the geological work for Snowden & McSweeney Company, at Fort Worth.

G. L. ELLIS represents the Snowden & McSweeney Company at Moab, Utah.

HARVE LOOMIS, consulting geologist, is now located at Baird, Texas.

EUGENE HOLMAN, chief geologist of the Humble Oil & Refining Company, spent his vacation in September near Chicago.

CLYDE M. BENNETT, vice-president of the Louisiana Oil Refining Corporation of Shreveport, spent September in the North.

R. D. VERNON is chief geologist for the Mexican Eagle Oil Company at Tampico.

E. BÖSE is working for the Standard Oil Company of California in northern Mexico.

N. F. DRAKE, of Fayetteville, Arkansas, has retired from his practice as consulting geologist.

WILLIAM MORRIS DAVIS, emeritus professor of Physiography at Harvard University, and Gilbert D. Harris, professor of Paleontology at Cornell University, will lecture at the University of Texas this winter.

CHARLES SCHUCHERT, emeritus professor of Paleontology at Yale University, will lecture at the University of Washington this winter.

HENRY HINDS is representing the Agwi at Maracaibo.

CALVIN T. MOORE, chief geologist of the Coline Oil Company at Oklahoma City, has been working in southern Louisiana. C. F. BUCHNER has been in charge of the office during his absence.

E. P. PHILBRICK, formerly geologist with the Continental Oil Company, is now with the White Eagle Oil & Refining Company at Fort Worth.

R. A. CONKLING, consulting geologist at Oklahoma City, has been working in Jack County, Texas.

C. W. HONESS located the gas well of the Empire Gas & Fuel Company in Johnson County, Arkansas, northwest of Clarksville.

FRANK GOUIN, of Duncan, Oklahoma, has developed deeper production in the South Duncan oil field.

R. C. QUIETT and FRANK P. LATIMER, of the Indian Territory Illuminating Oil Company, discovered *Monograptus* in cuttings from the Independent-Garland well in Sec. 26, T. 9 N., R. 6 E., Oklahoma, which proved that the well was drilling in the Sylvan shale and "running high," and enabled them to purchase an interest in the royalty before the well reached the Wilcox sand.

DARWIN M. BENEDUM, of Pittsburgh, Pennsylvania, represents the Pittsburgh Development Company at San Antonio, Texas.

THOMAS H. KERNAN, geologist for the McBride estate, has headquarters at 704 Shell Building, St. Louis, Missouri.

EMERSON M. PARKS is engaged in consulting practice at Amarillo, Texas.

C. L. COOPER has been appointed assistant director of the Oklahoma Geological Survey.

FRANK E. KENDRICK is chief geologist for the Lone Star Gas Company of Dallas.

A. E. FATH spent November and December on a foreign trip.

J. P. McCULLOCH has resigned from the Gulf Oil Corporation to accept a position in South America with the Sinclair Consolidated Oil Company.

E. B. WILSON, formerly with the Humphreys Corporation, is now employed by the Sun Oil Company of Dallas.

L. G. DONNELLY has moved to Santa Fe, New Mexico.

R. VAN A. MILLS, of the U. S. Bureau of Mines, has been transferred to Bartlesville, Oklahoma, for a research assignment.

THERON WASSON, chief geologist of the Pure Oil Company of Chicago, Illinois, addressed the Tulsa Geological Society in October on Bolivia.

THOMAS GEORGE MADGWICK, consulting oil geologist, is temporarily retained by the Canadian Department of the Interior as petroleum engineer at Calgary, Alberta.

A. R. DENISON, geologist for the Amerada Petroleum Corporation, has been transferred from Enid to Tulsa.

N. H. DARTON, of the U. S. Geological Survey, has returned to Washington after spending a summer in areal mapping in West Texas.

C. E. DOBBIN, A. A. BAKER, and E. T. MCKNIGHT, of the U. S. Geological Survey, have returned to Washington after a season spent in structural and stratigraphic work in southeastern Utah.

C. L. SEVERY, consulting geologist at Tulsa, discovered the new gas field on the Smelter anticline east of Van Buren, Crawford County, Arkansas. The discovery well of the Industrial Oil & Gas Company is located in NE.  $\frac{1}{4}$ , NW.  $\frac{1}{4}$ , NE.  $\frac{1}{4}$ , Sec. 22, T. 9 N., R. 31 W., depth 1,250 feet. The original Kibbler gas field discovery well, drilled in 1915, was located in Sec. 31, T. 9 N., R. 30 W. The Alma gas field was opened in 1923 by a well located in Sec. 7, T. 9 N., R. 30 W. The Alma extension field was opened in 1925 by a well in Sec. 4 of the same township.

J. S. IRWIN has resigned as chief geologist for the Producers & Refiners Corporation to accept a similar position with the F. E. Kistler Oil Company of Denver.

W. B. WILSON, chief geologist of the Gypsy Oil Company of Tulsa, made his annual trip to Pittsburgh in October.

D. R. SNOW, chief geologist of the Barnsdall Oil Company of Tulsa, investigated the oil possibilities of Wyoming in October.

FLOYD DODSON, of the El Capitan Oil Company, spent September and October in California.

G. E. EBMEYER is in the employ of George Williams at Amarillo.

WALTER BURRESS, of the Mid-Continent Petroleum Company, has been transferred to Abilene, Texas.

ALEXANDER MILYKO, of the Texas Company, is stationed at San Angelo, Texas.

HJALMAR ABRAHAMSON is living at the Texas Hotel, Fort Worth.

RICHARD T. LYONS, of the Skelly Oil Company, has moved to San Angelo.

A. H. NOBLE, of the Dutch Shell, is in charge of their geologic operations at Sarawak, East Indies.

H. H. ADAMS, of Fort Worth, discovered the new Wyndam oil field west of Cross Plains, Texas.

F. O. REYNOLDS, formerly with the Indian Territory Illuminating Oil Company at Roswell, New Mexico, has joined the geological department of the Amerada Petroleum Corporation at Amarillo, Texas.

L. E. OLES is in charge of the geological work of the Prairie at Amarillo.

PAUL OLES represents the Prairie Oil & Gas Company at Wichita Falls.

MORGAN DAVIS is in charge of the geological work of the Humble Oil & Refining Company at Roswell, New Mexico.

PAUL MCEWAN, represents the Midwest Refining Company at Roswell.

RAYMOND M. CARR, of the Sinclair Oil & Gas Company, is working at Covington, Oklahoma.

The following members of the Association were on the program at the meetings of the Mid-Continent section of the American Society of Mechanical Engineers, held October 28 and 29 at Tulsa: CHARLES R. ECKES, R. S. MCFARLAND, and JOHN M. LOVEJOY.

At the meetings of the Petroleum Division of the American Institute of Mining and Metallurgical Engineers, October 11 and 12, 1926, at Tulsa, Oklahoma, the following members of the Association were on the program: JAMES O. LEWIS, R. P. McLAUGHLIN, CHARLES E. BEECHER, F. W. DEWOLF, JAMES A. GARDNER, W. T. THOM JR., STANLEY C. HEROLD, JOHN R. SUMAN, MAX BAUER, and H. B. HILL.

MAX W. BALL, E. RUSSELL LLOYD, T. S. HARRISON, and T. H. OLDS of Denver, visited Ponca City and Tulsa late in October.

L. CLARK MORGAN, formerly of the Sinclair Oil & Gas Company, is now head of the geological department of the Kansas City, Mexico, and Orient Railway Company, and is engaged in an exploratory trip through northern Chihuahua, Mexico.

The discovery well of the Pure Oil Company at Sweet Lake, Cameron Parish, Louisiana, 5,897 feet deep, was located on gas seepages and confirmed as a buried Miocene hill by seismographic work.

C. A. CHENEY, consulting geologist in Tulsa, has moved to the Ritz building.

R. S. TARR is associated with FRANK GILLESPIE in the National Bank of Commerce Building, Tulsa.

J. J. VICTOR lives at the New Willard Hotel, Tulsa, Oklahoma.

KIRK WHITE is geologist for the Dixie Oil Company of Tulsa.

E. A. WYMAN, of the Amerada Petroleum Corporation, has been transferred to Wichita Falls, Texas.

## Memorial

### CHARLES STIRLING HUNTLEY

To those of us who knew Stirling Huntley personally the news of his tragic death on May 26, 1926, was a bitter shock. To his hundreds of professional brothers who knew him through his work the news was hardly less distressing. The splendid assistance of his friends and their willingness to serve in the days immediately following his death bore tribute to the character of friendships which he created. The death of a young man is always grievous, but when that life holds a brilliant future it is a tragedy. The wilful and needless sacrifice of this life loses to his many friends and the American Association of Petroleum Geologists a lovable character, a splendid comrade, and an exceptionally able mind.

Stirling Huntley was born at Emsworth, Pennsylvania, November 24, 1895, the son of Charles Louis and Antoinette (Grow) Huntley of American colonial ancestry. He began his higher education at the University of Michigan, where was a student from 1914 to 1916. The following year he began the intensive study of petroleum geology at the University of Pittsburgh, from which he received the degree of B.S., in 1920, after the interruption of the war. While still a student he had a large amount of practical field work in the oil districts of New York, Pennsylvania, and West Virginia. Soon after the declaration of war he enlisted in the Engineering Corps of the army and saw active service in France with Company D of 104th Engineers, 29th Division A. E. F.

Following his return from France and the completion of his studies, he went to Mexico as chief geologist of the Island Oil and Transport Company. It was during this time that his aptitude for foreign work was developed. The many original problems involved in exploratory work became a hobby, and in subsequent years the experiences of this period of his life were of great advantage.

In 1922, with his older brother, Louis G. Huntley, Stirling formed a partnership of consulting geologists under the name of Huntley and Huntley, with offices at Pittsburgh. As a member of that firm he built up an enviable reputation for clear and capable thought together with unquestioned integrity.

The business of consulting geologist gave him a varied experience in all parts of the oil-producing districts of the United States and carried him on extensive trips into Venezuela, Colombia, and Mexico. In this country he is best known for his studies in California, Louisiana, west and south Texas. He was engaged in this last work when he met his untimely death at the hands of bandits near Laredo, Texas.

Stirling Huntley's was an engaging character. His very quiet demeanor was baffling to new acquaintance, but, as friendship progressed, was found to mask, not an indifference, but a keen perception and ready understanding. His abundant fund of dry humor will always be remembered by his friends. Fearless in the pursuit of an ideal and tireless in the achievement of an ambition, he bequeathed to the profession an enviable example.

His widow and an infant son, Stirling Jr., survive him.

J. EARLE BROWN

## INDEX TO VOLUME 10

[NOTE.—Page numbers up to 642 refer to articles in Part 1 of Volume 10 (Numbers 1-6); those above 642 refer to articles in Part 2 (Numbers 7-12).]

|   | PAGE   |
|---|--|
| Age of Producing Horizon, Rice County, Kansas. Geological Note by Henry A. Ley . . . . .  | 197  |
| Alteration, Porosity and Crushing Strength as Indices of Regional. By W. L. Russell . . . . .   | 939  |
| American Association of Petroleum Geologists, Eleventh Annual Meeting of The. By E. DeGolyer, W. E. Wrather, Charles E. Decker, Raymond C. Moore, C. R. McCollom. The Association Round Table . . . . . | 534  |
| American Chemical Society—Lubrication Symposium Reprints. The Association Round Table . . . . .   | 1002   |
| Anderson, F. M. Original Source of Oil in Colombia. . . . .   | 382  |
| Anderson, Robert. Observations on the Occurrence and Origin of Petroleum in Argentine and Bolivia . . . . .   | 853  |
| Annual Meeting for 1927 to Be Held in Tulsa. The Association Round Table . . . . .  | 640  |
| Applin, E. R., and J. A. Cushman. Texas Jackson Foraminifera . . . . .  | 154  |
| Appointment of Business Manager. By Alex W. McCoy. The Association Round Table . . . . .  | 815  |
| Argentine and Bolivia, Observations on the Occurrence and Origin of Petroleum in. By Robert Anderson . . . . .  | 853  |
| Arizona and New Mexico, The Permian of. By N. H. Darton . . . . .   | 819  |
| Arkansas, Oil-Bearing Formations of Southwestern. U. S. Geological Survey Press Bulletin 8823. Review . . . . .   | 1310   |
| Association Round Table, The . . . . .  | 100, 201, 316, 453, 534, 640, 815, 909, 1001, 1178, 1313 |
| At Home and Abroad . . . . .  | 103, 360, 454, 550, 641, 730, 817, 1005, 1184, 1316      |
| Aurin, F. L., H. G. Officer, and Glenn C. Clark. Core Drilling for Structure in the North Mid-Continent Area. . . . .   | 513  |
| Aurin, Fritz. Membership Applications Approved for Publication. The Association Round Table . . . . .   | 534  |
| Aurin, F. L., H. G. Officer, and Charles N. Gould. The Subdivision of the Enid Formation. . . . .   | 786  |
| Balcones and Mexia Faulting, Mechanics of the. By Lyndon L. Foley . . . . .   | 1261   |
| Baldwin Hills, Los Angeles County, California, The Pliocene and Pleistocene History of the. By A. J. Tiejé . . . . .  | 502  |
| Ball, Max W. Geophysics at Colorado School of Mines. Geological Note . . . . .  | 1306   |

|  | PAGE |
|--|------|
| Ball, Max W., John L. Rich, and J. P. D. Hull. The Denver Meeting.<br>The Association Round Table . . . . .  | 1179 |
| Barometric Leveling. Geological Note by Henry A. Ley . . . . .   | 1305 |
| Barton, Donald C., and R. H. Goodrich. The Jennings Oil Field, Acadia<br>Parish, Louisiana . . . . .   | 72   |
| Barton, Donald C. The Wigglegstick. Geological Note . . . . .  | 312  |
| Bartram, John G. Occurrence of Black Oil in Wyoming . . . . .  | 444  |
| Bauer, C. Max. Oil and Gas Fields of the Texas Panhandle . . . . .   | 733  |
| Beckstrom, R. C., and F. M. Van Tuyl, The Effect of Pressure on the<br>Migration and Accumulation of Petroleum . . . . .                                   | 917  |
| Berkey, Charles P. The Geological Society of America. The Associa-<br>tion Round Table . . . . .   | 453  |
| Bexar County, Texas, Subsurface Cretaceous Section of Southwest. By<br>Richard A. Jones . . . . .  | 768  |
| Big Lake Oil Field, The Subsurface Geology of the. By E. H. Sellards<br>and Leroy T. Patton . . . . .  | 365  |
| Black Hills Region, Oil Possibilities of the. Discussion by W. W. Rubey . . . . .  | 1177 |
| Black Hills Region, Oil Possibilities of the. By E. G. Sinclair . . . . .  | 800  |
| Black Oil in Wyoming, Occurrence of. By John G. Bartram . . . . .  | 444  |
| Bloesch, Edward. Fort Scott-Wetumka Correlation. Geological Note . . . . .   | 810  |
| ———. Oil Mining . . . . .  | 405  |
| Bolivia, Observations on the Occurrence and Origin of Petroleum in<br>Argentina and. By Robert Anderson . . . . .  | 853  |
| Brown, J. Earle. Memorial of Charles Stirling Huntley . . . . .  | 1322 |
| Brown, J. S., and C. L. Dake. Interpretation of Topographic and<br>Geologic Maps. Review by K. C. Heald . . . . .  | 906  |
| Buried Hills near Mannsville, Oklahoma. By C. W. Tomlinson . . . . .   | 138  |
| Buried Hills, Reflected, in the Oil Fields of Persia, Egypt, and Mexico.<br>By Sidney Powers . . . . .   | 422  |
| Business Manager, Appointment of. By Alex W. McCoy. The Associa-<br>tion Round Table . . . . .   | 815  |
| Bybee, H. P., and R. T. Short. The Lytton Springs Oil Field. The<br>Bureau of Economic Geology of the University of Texas, Bull. 2539.<br>Review . . . . . | 314  |
| Cadman, W. K. A Phantograph Model. Geological Note . . . . .   | 1300 |
| California, Observations Relating to the Origin and Accumulation of<br>Oil in. By G. C. Gester . . . . .   | 892  |
| California Oil, Were Diatoms the Chief Source of? By George M.<br>Cunningham . . . . .   | 709  |
| California Petroleum, The Relation of Foraminifera to the Origin of.<br>By Thomas F. Stipp. . . . .  | 697  |
| California, The Pliocene and Pleistocene History of the Baldwin Hills,<br>Los Angeles County. By A. J. Tieje . . . . .                                     | 502  |

# INDEX TO VOLUME 10

1325

|   | PAGE |
|---|------|
| China, Oil Prospects in Northeastern. By Myron L. Fuller and Frederick G. Clapp . . . . .   | 1073 |
| Clapp, Frederick G., and Myron L. Fuller. Oil Prospects in Northeastern China . . . . .   | 1073 |
| Clapp, Frederick G. and Myron L. Fuller. Oil Fields in China: Acknowledgements and Correlations. Geological Note . . . . .  | 449  |
| Clapp, Frederick G. New Zealand Oil Discovery. Geological Note . . . . .  | 451  |
| ———. Oil and Gas Prospects of New Zealand . . . . .   | 1227 |
| ———. Oil Prospects of the Desert Basin of Western Australia . . . . .   | 1118 |
| ———. Oil Prospects of the Northwest Basin of Western Australia . . . . .  | 1136 |
| Clark, Glenn C., H. G. Officer, and F. L. Aurin. Core Drilling for Structure in the North Mid-Continent Area. . . . .   | 513  |
| Clark, Glenn C. Wilcox Sand Production, Tonkawa Field, Oklahoma . . . . .   | 885  |
| Clark, Stuart K. Thomas Oil Field, Kay County, Oklahoma . . . . .   | 643  |
| Coast Ranges, Miocene Paleogeography in the Central. By R. D. Reed . . . . .  | 130  |
| Collingwood, D. M., and R. E. Rettger. The Lytton Springs Oil Field, Caldwell County, Texas . . . . .   | 953  |
| Collom, R. E. Review of Principles of Soil Mechanics, By Charles Terzaghi . . . . .   | 314  |
| Colombia, Original Source of Oil in. Discussion by Otto Stutzer . . . . .   | 1175 |
| Colombia, Original Source of Oil in. By F. M. Anderson . . . . .  | 382  |
| Comanchean Strata of Central Kansas, New Data on the. By W. H. Twenhofel and A. C. Tester . . . . .   | 553  |
| Combined Geologic and Oil-and-Gas Map of Wyoming. Geological Note . . . . .   | 812  |
| Committees for the Autumn Meetings of the Association. The Association Round Table . . . . .  | 815  |
| Continental Drift, Discussion of, at Meeting November 15-17. By W. A. J. M. van Waterschoot van der Gracht. The Association Round Table . . . . .                         | 1002 |
| Coral Reefs in the Oligocene of Texas. By Alva Christine Ellisor . . . . .  | 976  |
| Cordilleran Branch of the Geological Society of America, Annual Meeting of the. Geological Note by K. C. Heald . . . . .  | 449  |
| Core Drilling for Structure in the North and Mid-Continent Area. By H. G. Officer, Glenn C. Clark, and F. L. Aurin . . . . .  | 513  |
| Correlation by Means of Foraminifera, Methods of. By J. J. Galloway . . . . .   | 562  |
| Correlation of the Permian of Kansas, Oklahoma, and Northern Texas. By Charles N. Gould . . . . .   | 144  |
| Correlative Value of the Microlithology and Micropaleontology of the Oil-Bearing Formations in the Sunset-Midway and Kern River Oil Fields. By Paul C. Goudkoff . . . . . | 482  |
| Cretaceous Section, of Southwest Bexar County, Subsurface. By Richard A. Jones . . . . .  | 768  |

|  | PAGE           |
|--|----------------|
| Cunningham, George M. The Wheeler Ridge Oil Field . . . . .  | 495            |
| ———. Were Diatoms the Chief Source of California Oil? . . . . .  | 709            |
| Currie Structure, Navarro County, Texas, Further Notes on the Origin<br>and Nature of the. By Frederic H. Lahee . . . . .  | 61             |
| Cushman, J. A., and E. R. Applin. Texas Jackson Foraminifera . . . . .   | 154            |
| Cushman, Joseph A. The Foraminifera of the Velasco Shale of the<br>Tampico Embayment . . . . .   | 581            |
| Cutler, Willard W., Jr. Predictions of the Future of Oil Pools by Early<br>Wells . . . . .   | 747            |
| Dake, C. L., and J. S. Brown. Interpretation of Topographic and Ge-<br>ologic Maps. Review by K. C. Heald . . . . .  | 906            |
| Darton, N. H. The Permian of Arizona and New Mexico . . . . .  | 819            |
| Decker, C. E. Membership Applications Approved for Publication.<br>The Association Round Table . . . . .   | 354            |
| ———. Membership List. The Association Round Table . . . . .  | 316            |
| Decker, Charles E., Raymond C. Moore, C. R. McCollom, E. DeGolyer,<br>W. E. Wrather. Eleventh Annual Meeting of the American Associa-<br>tion of Petroleum Geologists. The Association Round Table . . . . . | 537            |
| DeGolyer, E., W. E. Wrather, Charles E. Decker, Raymond C. Moore,<br>C. R. McCollom. Eleventh Annual Meeting of the American Associa-<br>tion of Petroleum Geologists. The Association Round Table . . . . . | 534            |
| Denison, A. R. Early Pennsylvanian Sediments West of the Nemaha<br>Granite Ridge, Kansas. Discussion . . . . .   | 636            |
| Denver Meeting, The. By Max W. Ball, John L. Rich, and J. P. D.<br>Hull. The Association Round Table . . . . .   | 1179           |
| Desert Basin of Western Australia, Oil Prospects of the. By Frederick<br>G. Clapp . . . . .  | 1118           |
| Deustua, Sr. R. A. Oil in Peru. Review by Frederic H. Lahee . . . . .  | 98             |
| DeWolf, F. W., and Paul T. Seashore. Diamond Drilling near Kerens,<br>Navarro County, Texas . . . . .  | 703            |
| Diamond Drilling near Kerens, Navarro County, Texas. By F. W. De-<br>Wolf and Paul T. Seashore . . . . .   | 703            |
| Diamond Drills and Diamond-Drill Equipment for Oil Structure In-<br>vestigation. By Robert Davis Longyear . . . . .  | 656            |
| Diatoms: Were They the Chief Source of California Oil? By George M.<br>Cunningham . . . . .  | 709            |
| Discussion . . . . .   | 636, 727, 1175 |
| Drop Auger, An Experiment with a. By Charles H. Row . . . . .  | 722            |
| Dues, Annual Membership. The Association Round Table . . . . .   | 1314           |
| Early Pennsylvanian Deposits West of the Nemaha Granite Ridge,<br>Kansas. By Raymond C. Moore . . . . .  | 205            |
| Early Pennsylvanian Sediments West of the Nemaha Granite Ridge,<br>Kansas. Discussion by A. R. Denison . . . . .   | 636            |

# INDEX TO VOLUME 10

1327

PAGE

|   |      |
|---|------|
| Eaton, J. E. A Contribution to the Geology of Los Angeles Basin, California . . . . .   | 753  |
| Egypt, Persia, and Mexico, Reflected Buried Hills in the Oil Fields of. By Sidney Powers . . . . .  | 422  |
| Ellisor, Alva Christine. Coral Reefs in the Oligocene of Texas . . . . .  | 976  |
| Enid Formation, The Subdivision of the. By F. L. Aurin, H. G. Officer, and Charles N. Gould . . . . .   | 786  |
| Eötvös Torsion Balance, Schweydar-Bamberg Types of. By C. A. Heiland . . . . .  | 1201 |
| Eötvös Torsion Balance, Torsion Balance Principles as Applied by the Original. By George Steiner . . . . .  | 1210 |
| Equal Pound Loss Method of Estimating Gas Reserves, A Critical Examination of the. By Roswell H. Johnson and L. C. Morgan . . . . .                       | 901  |
| Etched Potholes, The Bureau of Economic Geology of the University of Texas, Bull. 2509. By J. A. Udden. Review . . . . .                                  | 314  |
| Experiment with a Drop Auger, An. By Charles H. Row . . . . .   | 722  |
| Fall Meeting to be Held in New York City. The Association Round Table . . . . .   | 1002 |
| Faulting in the Rocky Mountain Region. By J. S. Irwin . . . . .   | 105  |
| Faulting, Mechanics of the Balcones and Mexia. By Lyndon L. Foley . . . . .   | 1261 |
| Faults in Creek and Osage Counties, Oklahoma, The Origin of the. By Lyndon L. Foley . . . . .   | 293  |
| Fisher, C. A. Review of Symposium on Petroleum Development and Technology in 1925 . . . . .   | 1261 |
| Fohs, F. Julius. Tulsa Meeting of the American Institute of Mining and Metallurgical Engineers, Petroleum Division. The Association Round Table . . . . . | 911  |
| Foley, Lyndon L. Mechanics of the Balcones and Mexia Faulting . . . . .   | 1261 |
| ———. The Origin of the Faults in Creek and Osage Counties, Oklahoma . . . . .   | 293  |
| Foraminifera, Methods of Correlation by Means of. By J. J. Galloway . . . . .   | 562  |
| Foraminifera of the Velasco Shale of the Tampico Embayment, The. By Joseph A. Cushman . . . . .   | 581  |
| Foraminifera, Short Cuts in Picking Out and Sectioning. Geological Note by Floyd and Helen Hodson . . . . .   | 1173 |
| Foraminifera, Texas Jackson. By J. A. Cushman and E. R. Applin . . . . .  | 154  |
| Foraminifera, The Relation of, to the Origin of California Petroleum. By Thomas F. Stipp . . . . .  | 697  |
| Fordham, W. H. Oil Finding by Geophysical Methods. Review by Frederic H. Lahee . . . . .  | 200  |
| Fort Scott-Wetumka Correlation. Geological Note by Edward Bloesch . . . . .   | 810  |
| Fuller, Myron L., and Frederick G. Clapp. Oil Prospects in Northeastern China . . . . .   | 1073 |
| Fuller, Myron L., and Frederick G. Clapp. Oil Fields in China: Acknowledgements and Correlations. Geological Note . . . . .                               | 449  |

|  | PAGE |
|--|------|
| Galloway, J. J. Methods of Correlation by Means of Foraminifera . . .  | 562  |
| Gas and Oil near Edna, Jackson County, Texas. Geological Note by<br>W. Armstrong Price . . . . .   | 905  |
| Gas Reserves, A Critical Examination of the Equal Pound Loss Method<br>of Estimating. By Roswell H. Johnson and L. C. Morgan . . . . .   | 901  |
| Geological Notes . . . . . 93, 197, 312, 449, 531, 634, 810, 905, 997, 1171, 1300  |      |
| Geological Society of America, Meeting of the. By K. C. Heald. The<br>Association Round Table . . . . .  | 100  |
| Geological Society of America, Meeting of the. By W. H. Twenhofel.<br>The Association Round Table . . . . .  | 534  |
| Geological Society of America, The. By Charles P. Berkey. The Associa-<br>tion Round Table . . . . .   | 453  |
| Geologic History of the Panuco River Valley and Its Relation to the<br>Origin and Accumulation of Oil in Mexico. By Earl A. Trager . . . . .                                   | 667  |
| Geologic Structure of a Portion of the Glass Mountains of West Texas,<br>The. By Philip B. King . . . . .  | 877  |
| Geology of the Oil Fields in North (Russian) Sakhalin, Preliminary Re-<br>port on the. By Giichiro Kobayashi . . . . .   | 1150 |
| Geology and Oil Fields of Archer County, Texas, The. By W. E. Hub-<br>bard and W. C. Thompson . . . . .  | 457  |
| Geology of Los Angeles Basin, California, A Contribution to the. By<br>J. E. Eaton . . . . .   | 753  |
| Geophysics at Colorado School of Mines. Geological Note by Max W.<br>Ball . . . . .  | 1306 |
| Gester, G. C. Observations Relating to the Origin and Accumulation of<br>Oil in California . . . . .   | 892  |
| Glass Mountains of West Texas, The Geologic Structure of a Portion of<br>the. By Philip B. King . . . . .  | 877  |
| Goodrich, R. H., and Donald C. Barton. The Jennings Oil Field, Acadia<br>Parish, Louisiana . . . . .   | 72   |
| Goudkoff, Paul D. Correlative Value of the Microlithology and Micro-<br>paleontology of the Oil-Bearing Formations in the Sunset-Midway<br>and Kern River Oil Fields . . . . . | 482  |
| Gould, Charles N., H. G. Officer, and F. L. Aurin. The Subdivision of the<br>Enid Formation. . . . .   | 786  |
| Gould, Charles N. Oklahoma Survey, Seventh Field Conference.<br>Ouachita Mountains of Oklahoma. Geological Note . . . . .  | 1305 |
| ———. Review of New Publications, Oklahoma Geological Survey . . . . .  | 1311 |
| ———. The Correlation of the Permian of Kansas, Oklahoma, and<br>Northern Texas. . . . .  | 144  |
| Granite Ridge of Kansas, The. Geological Note by Henry A. Ley . . . . .  | 95   |
| Gravitational Compaction on the Structure of Sedimentary Rocks, The<br>Effect of. By Hollis D. Hedberg . . . . .   | 1035 |

# INDEX TO VOLUME 10

1329

|  | PAGE                  |
|--|-----------------------|
| Hamilton, Henry L. Memorial by W. R. Hamilton . . . . .  | 358                   |
| Hamilton, W. R. Memorial of Henry L. Hamilton . . . . .  | 358                   |
| Hammer, A. A., and A. M. Lloyd. Notes on the Quadrant Formation of<br>East-Central Montana . . . . .                     | 986                   |
| Hanna, G. D., and J. A. Taff. Notes on the Age and Correlation of the<br>Moreno Shale. Geological Note . . . . .         | 812                   |
| Hanna, Marcus A. An Interesting Volcanic Ash from Calcasieu Parish,<br>Louisiana. Geological Note . . . . .              | 93                    |
| Hauerite in a Salt-Dome Cap Rock. Geological Note by Albert G. Wolf  | 531                   |
| Heald, K. C. Annual Meeting of the Cordilleran Branch of the Geological<br>Society of America. Geological Note . . . . . | 449                   |
| ———. Meeting of the Geological Society of America. The Association<br>Round Table . . . . .                              | 100                   |
| ———. Review of Structure in North Haakon County, by Freeman<br>Ward . . . . .  | 533                   |
| ———. Review of The Possibility of Oil in Western Ziebach County,<br>by William L. Russell . . . . .                      | 638                   |
| ———. Review of Interpretation of Topographic and Geologic Maps, by<br>C. L. Dake and J. S. Brown . . . . .               | 906                   |
| ———. The Kevin-Sunburst Oil Field, Montana. Geological Note . .  | 197                   |
| Hedberg, Hollis D. The Effect of Gravitational Compaction on the<br>Structure of Sedimentary Rocks . . . . .             | 1035                  |
| Heiland, C. A. Construction, Theory, and Application of Magnetic Field<br>Balances . . . . .                             | 1189                  |
| ———. Schweydar-Bamberg Types of Eötvös Torsion Balance . . . .   | 1201                  |
| Hendon, Bryan. Memorial by Claude Hendon . . . . .   | 1188                  |
| Hendon, Claude. Memorial of Bryan Hendon . . . . .   | 1188                  |
| Hinds, Henry. Unconformities in the Pennsylvanian. Geological Note   | 1303                  |
| Hodson, Floyd and Helen. Short Cuts in Picking Out and Sectioning<br>Foraminifera. Geological Note . . . . .             | 1173                  |
| Howe, James V. Memorial by J. H. Jenkins . . . . .   | 1188                  |
| Hubbard, W. E., and W. C. Thompson. The Geology and Oil Fields of<br>Archer County, Texas . . . . .                      | 457                   |
| Hudson, F. S., and N. L. Taliaferro, An Interesting Example of a Survey<br>of a Deep Bore Hole . . . . .                 | 775                   |
| Hull, J. P. D. Discovery of Nigger Creek Oil Pool, Limestone County,<br>Texas. Geological Note . . . . .                 | 997                   |
| Hull, J. P. D., Max W. Ball, and John L. Rich. The Denver Meeting.<br>The Association Round Table . . . . .              | 1179                  |
| Hull, J. P. D. Membership Applications Approved for Publication. The<br>Association Round Table. . . . .                 | 909, 1001, 1178, 1313 |
| Huntley, Charles Stirling. Memorial by J. Earle Brown . . . . .  | 1322                  |

|   | PAGE |
|---|------|
| Ickes, E. L. Origin of the Faults in Creek and Osage Counties, Oklahoma. Discussion . . . . .   | 727  |
| Interior Salt Domes of Louisiana. By W. C. Spooner . . . . .  | 217  |
| Interior Salt Domes of Texas. By Sidney Powers . . . . .  | 1    |
| International Geological Congress, Announcements of the Fourteenth. The Association Round Table . . . . .                               | 201  |
| Interpretation of Topographic and Geologic Maps. By C. L. Dake and J. S. Brown. Review by K. C. Heald . . . . .                         | 906  |
| Irwin, J. S. Faulting in the Rocky Mountain Region . . . . .  | 105  |
| Jackson Foraminifera, Texas. By J. A. Cushman and E. R. Applin . . . . .  | 154  |
| Jenkins, J. H. Memorial of James V. Howe . . . . .  | 1188 |
| Jennings Oil Field, Acadia Parish, Louisiana, The. By Donald C. Barton and R. H. Goodrich . . . . .                                     | 72   |
| Johnson, Roswell H., and L. C. Morgan. A Critical Examination of the Equal Pound Loss Method of Estimating Gas Reserves . . . . .       | 901  |
| Joint Meeting with the Rocky Mountain Section of the A. I. M. M. E. and American Mining Congress. The Association Round Table . . . . . | 640  |
| Jones, Richard A. Subsurface Cretaceous Section of Southwest Bexar County, Texas . . . . .  | 768  |
| Kansas, Age of Producing Horizon, Rice County. Geological Note by Henry A. Ley . . . . .  | 197  |
| ———. Early Pennsylvanian Deposits West of the Nemaha Granite Ridge. By Raymond C. Moore . . . . .                                       | 205  |
| ———. Early Pennsylvanian Sediments West of the Nemaha Granite Ridge. Discussion by A. R. Denison . . . . .                              | 636  |
| ———. Eastern, Further Observations on Shoestring Oil Pools of. By John L. Rich . . . . .  | 568  |
| ———. Mississippi Lime West of the Granite Ridge in. Geological Note by Henry A. Ley . . . . .   | 96   |
| ———. New Data on the Comanchean Strata of Central. By W. H. Twenhofel and A. C. Tester . . . . .  | 553  |
| ———. Occurrence of Ordovician Sediments in Western. Geological Note by Jon A. Udden . . . . .   | 634  |
| ———. Oklahoma, and Northern Texas, The Correlation of the Permian of. By Charles N. Gould . . . . .                                     | 144  |
| ———. The Granite Ridge of. Geological Note by Henry A. Ley . . . . .  | 95   |
| ———. The Sheridan Test, Ellsworth County. Geological Note by Henry A. Ley . . . . .   | 199  |
| Kendrick, Frank E. Memorial of William Kennedy . . . . .  | 913  |
| Kennedy, William. Memorial by Frank E. Kendrick . . . . .   | 913  |
| Kevin-Sunburst Oil Field, Montana. Geological Note by K. C. Heald . . . . .   | 197  |

# INDEX TO VOLUME 10

1331

PAGE

|   |      |
|---|------|
| King, Philip B. The Geologic Structure of a Portion of the Glass Mountains of West Texas . . . . .  | 877  |
| Kobayashi, Giichiro. Preliminary Report on the Geology of the Oil Fields in North (Russian) Sakhalin . . . . .                                    | 1150 |
| Lahee, Frederic H. Some Features of Red-Bed Bleaching. Discussion . . . . .   | 636  |
| ———. Further Notes on the Origin and Nature of the Currie Structure, Navarro County . . . . .   | 61   |
| ———. Review of Oil Finding by Geophysical Methods, by W. H. Fordham . . . . .   | 200  |
| ———. Review of Oil in Peru, by Sr. R. A. Deustua . . . . .  | 98   |
| Lang, Walter B. A Soxhlet Extractor for Porosity Determinations. Geological Note. . . . .   | 998  |
| ———. Unusual Natural Gases. Discussion . . . . .  | 1176 |
| Ley, Henry A. Age of Producing Horizon, Rice County, Kansas. Geological Note . . . . .  | 197  |
| ———. Barometric Leveling. Geological Note . . . . .   | 1305 |
| ———. Mississippi Lime West of the Granite Ridge in Kansas. Geological Note . . . . .  | 96   |
| ———. The Granite Ridge of Kansas. Geological Note . . . . .   | 95   |
| ———. The Sheridan Test, Ellsworth County, Kansas. Geological Note . . . . .   | 199  |
| Library, The Association. The Association Round Table. . . . .  | 1314 |
| Lithologic Character of Shale as an Index of Metamorphism. By John H. Wilson. . . . .   | 615  |
| Lloyd, A. M., and A. A. Hammer. Notes on the Quadrant Formation of East-Central Montana . . . . .   | 986  |
| Longyear, Robert Davis. Diamond Drills and Diamond-Drill Equipment for Oil Structure Investigation . . . . .                                      | 656  |
| Los Angeles Basin, California, A Contribution to the Geology of. By J. E. Eaton . . . . .   | 753  |
| Louisiana, An Interesting Volcanic Ash from Calcasieu Parish. Geological Note by Marcus A. Hanna. . . . .   | 93   |
| ———. Interior Salt Domes of. By W. C. Spooner . . . . .   | 217  |
| ———. The Jennings Oil Field, Acadia Parish. By Donald C. Barton and R. H. Goodrich . . . . .  | 72   |
| Lubrication Symposium Reprints—American Chemical Society. The Association Round Table. . . . .  | 1003 |
| Lytton Springs Oil Field, Caldwell County, Texas, The. By D. M. Collingwood and R. E. Rettger . . . . .   | 953  |
| Lytton Springs Oil Field, The Bureau of Economic Geology of the University of Texas, Bull. 2539. By H. P. Bybee and R. T. Short. Review . . . . . | 314  |

|  | PAGE                  |
|--|-----------------------|
| Magnetic Field Balances, Construction, Theory, and Application of. By C. A. Heiland . . . . .  | 1189                  |
| McCollom, C. R., E. DeGolyer, W. E. Wrather, Charles E. Decker, Raymond C. Moore. Eleventh Annual Meeting of the American Association of Petroleum Geologists. The Association Round Table . . . . . | 537                   |
| McCoy, Alex W. A Brief Outline of Some Oil-Accumulation Problems . . . . .   | 1015                  |
| ———. Appointment of Business Manager. The Association Round Table . . . . .  | 815                   |
| McKee, Ralph H. Oil Shale. Review by John R. Reeves. . . . .   | 452                   |
| Membership Applications Approved for Publication. By C. E. Decker. The Association Round Table . . . . .   | 354                   |
| Membership Applications Approved for Publication. By Fritz Aurin. The Association Round Table . . . . .  | 534                   |
| Membership Applications Approved for Publication. By J. P. D. Hull. The Association Round Table . . . . .  | 909, 1001, 1178, 1313 |
| Membership List. By C. E. Decker. The Association Round Table . . . . .  | 316                   |
| Memorial . . . . .   | 358, 913, 1188, 1322  |
| Mexico, The Geologic History of the Panuco River Valley and Its Relation to the Origin and Accumulation of Oil in. By Earl A. Trager . . . . .   | 667                   |
| Mexico, Persia, and Egypt, Reflected Buried Hills in the Oil Fields of. By Sidney Powers . . . . .   | 422                   |
| Microlithology and Micropaleontology of the Oil-Bearing Formations in the Sunset-Midway and Kern River Oil Fields, Correlative Value of the. By Paul D. Goudkoff . . . . .                           | 482                   |
| Microthermal Observations of Some Oil Shales and Other Carbonaceous Rocks. By Taisia Stadnichenko and David White . . . . .  | 860                   |
| Migration and Accumulation of Petroleum, The Effect of Pressure on the. By F. M. Van Tuyl and R. C. Beckstrom . . . . .  | 917                   |
| Minnesota's Oil and Gas Possibilities. By Clinton R. Stauffer . . . . .  | 190                   |
| Miocene Paleogeography in the Central Coast Ranges. By R. D. Reed . . . . .  | 130                   |
| Mississippi Lime West of the Granite Ridge in Kansas. Geological Note by Henry A. Ley . . . . .  | 96                    |
| Montana, Notes on the Quadrant Formation of East-Central. By A. A. Hammer and A. M. Lloyd . . . . .  | 986                   |
| Moore, Raymond C., C. R. McCollom, E. DeGolyer, W. E. Wrather, Charles E. Decker. Eleventh Annual Meeting of the American Association of Petroleum Geologists. The Association Round Table . . . . . | 537                   |
| Moore, Raymond C. Early Pennsylvanian Deposits West of the Nemaha Granite Ridge, Kansas . . . . .  | 205                   |
| Moreno Shale, Notes on the Age and Correlation of the. Geological Note by J. A. Taff and G. D. Hanna . . . . .   | 812                   |
| Morgan, L. C., and Roswell H. Johnson. A Critical Examination of the Equal Pound Loss Method of Estimating Gas Reserves . . . . .  | 901                   |

# INDEX TO VOLUME 10

1333

PAGE

|   |      |
|---|------|
| Morse, Roy R. Meeting of the Pacific Section. The Association Round Table . . . . .   | 100  |
| Moulton, Gail F. Some Features of Red-Bed Bleaching . . . . .   | 304  |
| Natural Gases, Unusual. Discussion by Walter B. Lang . . . . .  | 1176 |
| Nemaha Granite Ridge, Kansas, Early Pennsylvanian Deposits West of the. By Raymond C. Moore . . . . .                       | 205  |
| New Mexico, The Permian of Arizona and. By N. H. Darton. . . . .  | 819  |
| New York City, Fall Meeting to be Held in. The Association Round Table . . . . .  | 1002 |
| New Zealand, Oil and Gas Prospects of. By Frederick G. Clapp . . . . .  | 1227 |
| New Zealand Oil Discovery. Geological Note by Frederick G. Clapp . . . . .  | 451  |
| Nigger Creek Oil Pool, Limestone County, Discovery of. Geological Note by J. P. D. Hull . . . . .                           | 997  |
| North Mid-Continent Area, Core Drilling for Structure in the. By H. G. Officer, Glenn C. Clark, and F. L. Aurin . . . . .   | 513  |
| Northwest Basin of Western Australia, Oil Prospects of the. By Frederick G. Clapp . . . . .                                 | 1136 |
| Occurrence and Origin of Petroleum in Argentina and Bolivia, Observations on the. By Robert Anderson . . . . .              | 853  |
| Officer, H. G., F. L. Aurin, and Charles N. Gould. The Subdivision of the Enid Formation . . . . .                          | 786  |
| Officer, H. G., Glenn C. Clark, and F. L. Aurin. Core Drilling for Structure in the North Mid-Continent Area . . . . .      | 513  |
| Oil-Accumulation Problems, A Brief Outline of Some. By Alex W. McCoy . . . . .  | 1015 |
| Oil and Gas Fields of the Texas Panhandle. By C. Max Bauer . . . . .  | 733  |
| Oil and Gas Prospects of New Zealand. By Frederick G. Clapp . . . . .   | 1227 |
| Oil-Bearing Formations of Southwestern Arkansas. U. S. Geological Survey Press Bulletin 8823. Review . . . . .              | 1310 |
| Oil Fields of China: Acknowledgements and Correlations. Geological Note by Frederick G. Clapp and Myron L. Fuller . . . . . | 449  |
| Oil Finding by Geophysical Methods. By W. H. Fordham. Review by Frederic H. Lahee . . . . .                                 | 200  |
| Oil in Colombia, Original Source of. By F. M. Anderson. . . . .   | 382  |
| Oil in Peru. By Sr. R. A. Deustua. Review by Frederic H. Lahee . . . . .  | 98   |
| Oil Mining. By Edward Bloesch . . . . .   | 405  |
| Oil Possibilities of the Black Hills Region. By E. G. Sinclair . . . . .  | 800  |
| Oil Possibilities of the Black Hills Region. Discussion by W. W. Rubey . . . . .  | 1177 |
| Oil Prospecting on Sakhalin Island by Japan in 1919-20, The Results of. By I. P. Tolmachoff . . . . .                       | 1163 |
| Oil Prospects of the Desert Basin of Western Australia. By Frederick G. Clapp . . . . .                                     | 1118 |

|  | PAGE |
|--|------|
| Oil Prospects in Northeastern China. By Myron L. Fuller and Frederick G. Clapp . . . . .   | 1073 |
| Oil Prospects of the Northwest Basin of Western Australia. By Frederick G. Clapp . . . . .   | 1136 |
| Oil Shale. By Ralph H. McKee. Review by John R. Reeves . . . . .   | 452  |
| Oil Shales and Other Carbonaceous Rocks, Microthermal Observations of Some. By Taisia Stadnichenko and David White . . . . .               | 860  |
| Oklahoma, Buried Hills near Mannsville, Oklahoma. By C. W. Tomlinson . . . . .   | 138  |
| Oklahoma Geological Survey, New Publications. Review by Charles N. Gould . . . . .   | 1311 |
| Oklahoma, Kansas, and Northern Texas, The Correlation of the Permian of. By Charles N. Gould. . . . .                                      | 144  |
| Oklahoma, Origin of the Faults in Creek and Osage Counties. Discussion by E. L. Ickes . . . . .  | 727  |
| Oklahoma Survey, Seventh Field Conference. Ouachita Mountains of Oklahoma. Geological Note by Charles N. Gould . . . . .                   | 1305 |
| Oklahoma, The Origin of the Faults in Creek and Osage Counties. By Lyndon L. Foley . . . . .   | 293  |
| ——. Thomas Oil Field, Kay County. By Stuart K. Clark . . . . .   | 643  |
| ——. Wilcox Sand Production, Tonkawa Field. By Glenn C. Clark . . . . .   | 885  |
| Oligocene of Texas, Coral Reefs in the. By Alva Christine Ellisor . . . . .  | 976  |
| Ordovician Sediments in Western Kansas, Occurrence of. Geological Note by Jon A. Udden . . . . .   | 634  |
| Origin and Accumulation of Oil in California, Observations Relating to the. By G. C. Gester . . . . .                                      | 892  |
| Origin of California Petroleum, The Relation of Foraminifera to the. By Thomas F. Stipp. . . . .   | 697  |
| Origin of the Faults in Creek and Osage Counties, Oklahoma. Discussion by E. L. Ickes . . . . .  | 727  |
| Origin of the Faults in Creek and Osage Counties, Oklahoma, The. By Lyndon L. Foley . . . . .  | 293  |
| Ouachita Mountains of Oklahoma, Oklahoma Survey Seventh Field Conference. Geological Note by Charles N. Gould . . . . .                    | 1305 |
| Pacific Section, Meeting of the. By Roy R. Morse. The Association Round Table . . . . .  | 100  |
| Panuco, Geologic History of the River Valley and Its Relation to the Origin and Accumulation of Oil in Mexico. By Earl A. Trager . . . . . | 667  |
| Patton, Leroy T., and E. H. Sellards. The Subsurface Geology of the Big Lake Oil Field . . . . .   | 365  |
| Patton, Leroy T. The Subsurface Geology of the Big Lake Oil Field . . . . .  | 304  |
| Pennsylvanian, Unconformities in the. Geological Note by Henry Hinds . . . . .   | 1303 |
| Permian of Arizona and New Mexico, The. By N. H. Darton . . . . .  | 819  |

# INDEX TO VOLUME 10

1335

|   | PAGE                                   |
|---|--|
| Permian of Kansas, Oklahoma, and Northern Texas, The Correlation of the. By Charles N. Gould . . . . .                  | 144                                    |
| Persia, Egypt, and Mexico, Reflected Buried Hills in the Oil Fields of. By Sidney Powers . . . . .                      | 422                                    |
| Peru, Oil in. By Sr. R. A. Deustua. Review by Frederic H. Lahee . . . . .   | 98                                     |
| Petroleum Development and Technology in 1925. Symposium. Review by C. A. Fisher . . . . .                               | 1309                                   |
| Phantograph Model, A. Geological Note by W. K. Cadman . . . . .   | 1300                                   |
| Pliocene and Pleistocene History of the Baldwin Hills, Los Angeles County, California, The. By A. J. Tieje . . . . .    | 502                                    |
| Porosity and Crushing Strength as Indices of Regional Alteration. By W. L. Russell . . . . .                            | 939                                    |
| Porosity, A Quick Method for Determining. By W. L. Russell . . . . .  | 931                                    |
| Possibility of Oil in Western Ziebach County, The. By William L. Russell. Review by K. C. Heald . . . . .               | 638                                    |
| Powers, Sidney. Interior Salt Domes of Texas . . . . .  | 1                                      |
| ———. Reflected Buried Hills in the Oil Fields of Persia, Egypt, and Mexico . . . . .                                    | 422                                    |
| Pratt, Wallace E. Two New Salt Domes in Texas. Geological Note . . . . .  | 1171                                   |
| Predictions of the Future of Oil Pools by Early Wells. By Willard W. Cutler, Jr. . . . .                                | 747                                    |
| Pressure, The Effect of on the Migration and Accumulation of Petroleum. By F. M. Van Tuyl and R. C. Beckstrom . . . . . | 917                                    |
| Price, W. Armstrong. Gas and Oil near Edna, Jackson County, Texas. Geological Note. . . . .                             | 905                                    |
| Principles of Soil Mechanics. By Charles Terzaghi. Review by R. E. Collom . . . . .                                     | 314                                    |
| Publication of Association Papers in Trade Journals. The Association Round Table . . . . .                              | 1004                                   |
| Publications, New, Oklahoma Geological Survey. Review by Charles N. Gould . . . . .                                     | 1311                                   |
| Quadrant Formation of East-Central Montana, Notes on the. By A. A. Hammer and A. M. Lloyd . . . . .                     | 986                                    |
| Red-Bed Bleaching, Some Features of. By Gail F. Moulton . . . . .   | 304                                    |
| Red-Bed Bleaching, Some Features of. Discussion by F. H. Lahee . . . . .  | 636                                    |
| Reed, R. D. Miocene Paleogeography in the Central Coast Ranges . . . . .  | 130                                    |
| Reeves, John R. Review of Oil Shale. By Ralph H. McKee . . . . .  | 452                                    |
| Regional Directors. By John L. Rich. The Association Round Table . . . . .  | 911                                    |
| Rettger, R. E., and D. M. Collingwood. The Lytton Springs Oil Field, Caldwell County, Texas . . . . .                   | 953                                    |
| Reviews . . . . .   | 98, 200, 314, 452, 533, 638, 906, 1309 |
| Revue de Géologie, The. Review by Adam Wroblewski . . . . .   | 98                                     |

|  | PAGE |
|--|------|
| Rich, John L. Further Observations on Shoestring Oil Pools of Eastern Kansas . . . . .   | 568  |
| Rich, John L., J. P. D. Hull, and Max W. Ball. The Denver Meeting. The Association Round Table . . . . .   | 1179 |
| Rich, John L. Regional Directors. The Association Round Table . . . . .  | 911  |
| Rocky Mountain Region, Faulting in the. By J. S. Irwin . . . . .   | 105  |
| Row, Charles H. An Experiment with a Drop Auger . . . . .  | 722  |
| Rubey, W. W. Oil Possibilities of the Black Hills Region. Discussion . . . . .   | 1177 |
| Russell, William L. The Possibility of Oil in Western Ziebach County. Review by K. C. Heald . . . . .  | 638  |
| ———. A Quick Method for Determining Porosity . . . . .   | 931  |
| ———. Porosity and Crushing Strength as Indices of Regional Alteration . . . . .  | 939  |
| Sakhalin Island, The Results of Oil Prospecting on by Japan in 1919-20. By I. P. Tolmachoff . . . . .  | 1163 |
| Sakhalin, Preliminary Report on the Geology of the Oil Fields in North (Russian). By Giichiro Kobayashi . . . . .                                    | 1150 |
| Salt Dome Cap Rock, Hauerite in a. Geological Note by Albert G. Wolf . . . . .   | 531  |
| Salt Domes in Texas, Two New. Geological Note by Wallace E. Pratt . . . . .  | 1171 |
| Salt Domes of Louisiana, Interior. By W. C. Spooner . . . . .  | 217  |
| Salt Domes of Texas, Interior. By Sidney Powers . . . . .  | 1    |
| Schweydar-Bamberg Types of Eötvös Torsion Balance. By C. A. Heiland . . . . .  | 1201 |
| Scott, Gayle. The Woodbine Sand of Texas Interpreted as a Regressive Phenomenon . . . . .  | 613  |
| Seashore, Paul T., and F. W. DeWolf. Diamond Drilling near Kerens, Navarro County, Texas . . . . .   | 703  |
| Sedimentary Rocks, The Effect of Gravitational Compaction on the Structure of. By Hollis D. Hedberg . . . . .  | 1035 |
| Sellards, E. H., and Leroy T. Patton. The Subsurface Geology of the Big Lake Oil Field . . . . .   | 365  |
| Shale, Lithographic Character of, as an Index of Metamorphism. By John H. Wilson . . . . .   | 615  |
| Sheridan Test, Ellsworth County, Kansas, The. Geological Note by Henry A. Ley . . . . .  | 199  |
| Shoestring Oil Pools of Eastern Kansas, Further Observations on. By John L. Rich . . . . .   | 568  |
| Short, R. T., and H. P. Bybee. The Lytton Springs Oil Field. The Bureau of Economic Geology of the University of Texas, Bull. 2539. Review . . . . . | 314  |
| Sinclair, E. G. Oil Possibilities of the Black Hills Region. . . . .   | 800  |
| Source of Oil in Colombia, Original. Discussion by Otto Stutzer . . . . .  | 1175 |

# INDEX TO VOLUME 10

1337

|  | PAGE |
|--|------|
| Soxhlet Extractor for Porosity Determinations, A. Geological Note by<br>Walter B. Lang . . . . .   | 998  |
| Spooner, W. C. Interior Salt Domes of Louisiana . . . . .  | 217  |
| Stadnichenko, Taisia, and David White. Microthermal Observations of<br>Some Oil Shales and Other Carbonaceous Rocks . . . . .  | 860  |
| Stauffer, Clinton R. Minnesota's Oil and Gas Possibilities . . . . .   | 190  |
| Steiner, George. Torsion Balance Principles as Applied by the Original<br>Eötvös Torsion Balance . . . . .   | 1210 |
| Stipp, Thomas F. The Relation of Foraminifera to the Origin of Cali-<br>fornia Petroleum . . . . .   | 697  |
| Structure in North Haakon County. By Freeman Ward. Review by<br>K. C. Heald . . . . .  | 533  |
| Structure of Sedimentary Rocks, The Effect of Gravitational Compac-<br>tion on the. By Hollis D. Hedberg . . . . .   | 1035 |
| Stutzer, Otto. Original Source of Oil in Colombia. Discussion. . . . .   | 1175 |
| Subsurface Geology of the Big Lake Oil Field, The. By E. H. Sellards<br>and Leroy T. Patton . . . . .  | 365  |
| Sunset-Midway and Kern River Oil Fields, Correlative Value of the<br>Microlithology and Micropaleontology of the Oil-Bearing Forma-<br>tions in the. By Paul D. Goudkoff . . . . . | 482  |
| Survey of a Deep Bore Hole, An Interesting Example of a. By F. S.<br>Hudson and N. L. Taliaferro . . . . .   | 775  |
| Taff, J. A., and G. D. Hanna. Notes on the Age and Correlation of the<br>Moreno Shale. Geological Note . . . . .   | 812  |
| Taliaferro, N. L., and F. S. Hudson. An Interesting Example of a Survey<br>of a Deep Bore Hole. . . . .  | 775  |
| Tampico Embayment, The Foraminifera of the Velasco Shale of the. By<br>Joseph A. Cushman . . . . .   | 581  |
| Terzaghi, Charles. Principles of Soil Mechanics. Review by R. E.<br>Collom . . . . .   | 314  |
| Tester, A. C., and W. H. Twenhofel. New Data on the Comanchean<br>Strata of Central Kansas. . . . .  | 553  |
| Texas, Coral Reefs in the Oligocene of. By Alva Christine Ellisor . . . . .  | 976  |
| ———. Diamond Drilling near Kerens, Navarro County. By F. W.<br>DeWolf and Paul T. Seashore . . . . .   | 703  |
| ———. Discovery of Nigger Creek Oil Pool, Limestone County. Geo-<br>logical Note by J. P. D. Hull . . . . .   | 997  |
| ———. Further Notes on the Origin and Nature of the Currie Structure,<br>Navarro County. By Frederic H. Lahee . . . . .   | 61   |
| ———. Gas and Oil near Edna, Jackson County. Geological Note by<br>W. Armstrong Price . . . . .   | 905  |
| ———. Interior Salt Domes of. By Sidney Powers . . . . .  | I    |
| Texas Jackson Foraminifera. By J. A. Cushman and E. R. Applin . . . . .  | 154  |

|   | PAGE |
|---|------|
| Texas, Northern, Kansas, and Oklahoma, The Correlation of the Permian of. By Charles N. Gould . . . . .   | 144  |
| Texas Panhandle, Oil and Gas Fields of the. By C. Max Bauer . . . . .   | 733  |
| Texas, Subsurface Cretaceous Section of Southwest Bexar County, By Richard A. Jones . . . . .   | 768  |
| ———. The Geologic Structure of a Portion of the Glass Mountains of West. By Philip B. King. . . . .   | 877  |
| ———. The Geology and Oil Fields of Archer County. By W. E. Hubbard and W. C. Thompson . . . . .   | 457  |
| ———. The Lytton Springs Oil Field, Caldwell County. By D. M. Collingwood and R. E. Rettger . . . . .  | 953  |
| ———. The Woodbine Sand of, Interpreted as a Regressive Phenomenon. By Gayle Scott . . . . .   | 613  |
| ———. Two New Salt Domes in. Geological Note by Wallace E. Pratt   | 1171 |
| Thomas Oil Field, Kay County, Oklahoma. By Stuart K. Clark . . . . .  | 643  |
| Thompson, W. C., and W. E. Hubbard. The Geology and Oil Fields of Archer County, Texas . . . . .  | 457  |
| Tieje, A. J. The Pliocene and Pleistocene History of the Baldwin Hills, Los Angeles County, California . . . . .  | 502  |
| Tolmachoff, I. P. The Results of Oil Prospecting on Sakhalin Island by Japan in 1919-20 . . . . .   | 1163 |
| Tomlinson, C. W. Buried Hills near Mannsville, Oklahoma . . . . .   | 138  |
| Tonkawa Field, Oklahoma, Wilcox Sand Production. By Glenn C. Clark  | 885  |
| Torsion Balance Principles as Applied by the Original Eötvös Torsion Balance. By George Steiner . . . . .   | 1210 |
| Trager, Earl A. The Geologic History of the Panuco River Valley and Its Relation to the Origin and Accumulation of Oil in Mexico. . . . .                   | 667  |
| Tulsa Meeting of the American Institute of Mining and Metallurgical Engineers, Petroleum Division. By F. Julius Fohs. The Association Round Table . . . . . | 911  |
| Twenhofel, W. H. and A. C. Tester, New Data on the Comanchean Strata of Central Kansas. . . . .   | 553  |
| Twenhofel, W. H. Meeting of the Geological Society of America. The Association Round Table. . . . .   | 534  |
| Udden, J. A. Etched Potholes, The Bureau of Economic Geology of the University of Texas, Bull. 2509. Review . . . . .                                       | 314  |
| Udden, Jon A. Occurrence of Ordovician Sediments in Western Kansas. Geological Note. . . . .  | 634  |
| U. S. Geological Survey Press Bull. 8823. Oil-Bearing Formations of Southwestern Arkansas. Review . . . . .   | 1310 |
| Unconformities in the Pennsylvanian. Geological Note by Henry Hinds   | 1303 |

# INDEX TO VOLUME 10

1339

PAGE

|  |      |
|--|------|
| Van der Gracht, W. A. J. M. van Waterschoot. Discussion of Continental Drift at Meeting November 15-17. The Association Round Table . . . . .  | 1002 |
| Van Tuyl, F. M., and R. C. Beckstrom. The Effect of Pressure on the Migration and Accumulation of Petroleum . . . . .  | 917  |
| Velasco Shale of the Tampico Embayment, The Foraminifera of the. By Joseph A. Cushman . . . . .  | 581  |
| Volcanic Ash from Calcasieu Parish, Louisiana, An Interesting Geological Note by Marcus A. Hanna. . . . .  | 93   |
| Ward, Freeman, Structure in North Haakon County. Review by K. C. Heald . . . . .   | 533  |
| Western Australia, Oil Prospects of the Desert Basin of. By Frederick G. Clapp . . . . .   | 1118 |
| Western Australia, Oil Prospects of the Northwest Basin of. By Frederick G. Clapp . . . . .  | 1136 |
| Wheeler Ridge Oil Field, The. By George M. Cunningham . . . . .  | 495  |
| White, David, and Taisia Stadnichenko. Microthermal Observations of Some Oil Shales and Other Carbonaceous Rocks . . . . .   | 860  |
| Wigglestick, The. Geological Note by Donald C. Barton . . . . .  | 312  |
| Wilcox Sand Production, Tonkawa Field, Oklahoma. By Glenn C. Clark . . . . .   | 885  |
| Wilson, John H. Lithologic Character of Shale as an Index of Metamorphism . . . . .  | 615  |
| Wolf, Albert G. Hauerite in a Salt-Dome Cap Rock. Geological Note . . . . .  | 531  |
| Woodbine Sand of Texas Interpreted as a Regressive Phenomenon, The. By Gayle Scott . . . . .   | 613  |
| Wrather, W. E., Charles E. Decker, Raymond C. Moore, C. R. McCollom, E. DeGolyer. Eleventh Annual Meeting of the American Association of Petroleum Geologists. The Association Round Table . . . . . | 537  |
| Wroblewski, Adam. Review of The Revue de Géologie . . . . .  | 98   |
| Wyoming, Combined Geologic and Oil-and-Gas Map of. Geological Note . . . . .   | 812  |
| ——. Occurrence of Black Oil in. By John G. Bartram . . . . .   | 444  |

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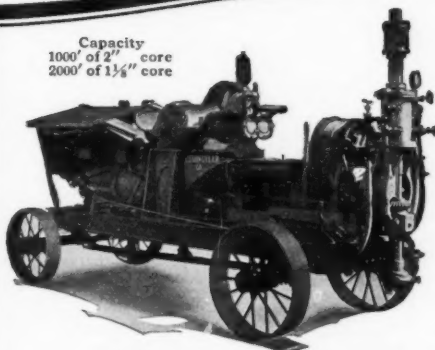
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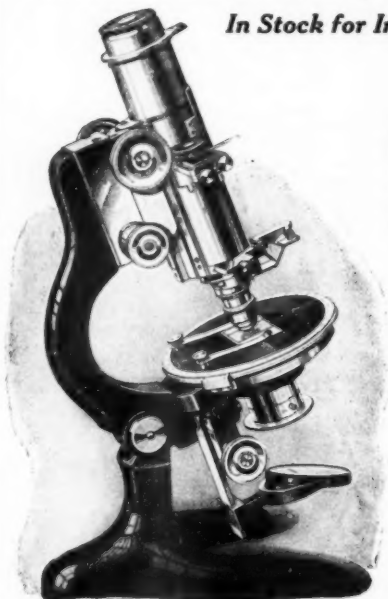
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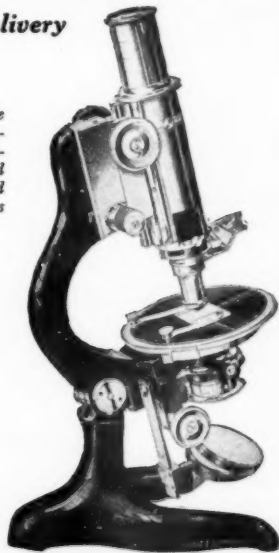
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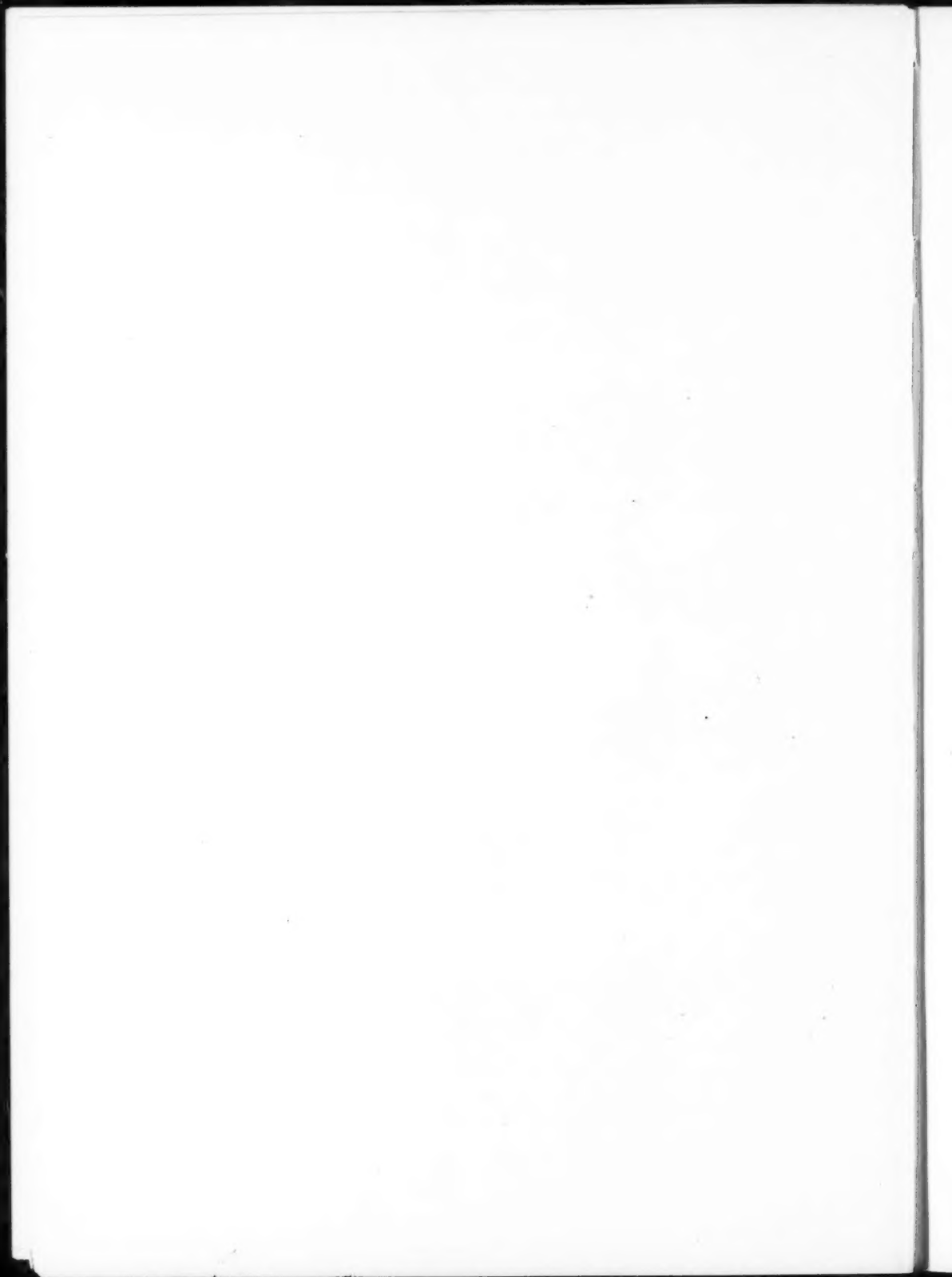
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PART 1  
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# CONTENTS OF VOLUME 10

## PART 1

### NUMBER 1

|  | PAGE |
|--|------|
| INTERIOR SALT DOMES OF TEXAS. Sidney Powers . . . . .  | I    |
| FURTHER NOTES ON THE ORIGIN AND NATURE OF THE CURRIE STRUCTURE, NAVARRO COUNTY, TEXAS. Frederic H. Lahee . . . . . | 61   |
| THE JENNINGS OIL FIELD, ACADIA PARISH, LOUISIANA. Donald C. Barton and R. H. Goodrich . . . . .                    | 72   |
| GEOLOGICAL NOTES   |      |
| An Interesting Volcanic Ash from Calcasieu Parish, Louisiana, <i>Marcus A. Hanna</i> . . . . .                     | 93   |
| The Granite Ridge of Kansas, <i>Henry A. Ley</i> . . . . .   | 95   |
| Mississippi Lime West of the Granite Ridge in Kansas, <i>Henry A. Ley</i> . . . . .                                | 96   |
| REVIEWS . . . . .  | 98   |
| THE ASSOCIATION ROUND TABLE . . . . .  | 100  |
| AT HOME AND ABROAD . . . . .   | 103  |

### NUMBER 2

|  |     |
|--|-----|
| FAULTING IN THE ROCKY MOUNTAIN REGION. J. S. Irwin . . . . .                                       | 105 |
| MIocene PALEOGEOGRAPHY IN THE CENTRAL COAST RANGES. R. D. Reed . . . . .                           | 130 |
| BURIED HILLS NEAR MANNVILLE, OKLAHOMA. C. W. Tomlinson . . . . .                                   | 138 |
| THE CORRELATION OF THE PERMIAN OF KANSAS, OKLAHOMA, AND NORTHERN TEXAS. Charles N. Gould . . . . . | 144 |
| TEXAS JACKSON FORAMINIFERA. J. A. Cushman and E. R. Applin . . . . .                               | 154 |
| MINNESOTA'S OIL AND GAS POSSIBILITIES. Clinton R. Stauffer . . . . .                               | 190 |
| GEOLOGICAL NOTES   |     |
| The Kevin-Sunburst Oil Field, Montana, <i>K. C. Heald</i> . . . . .                                | 197 |
| Age of Producing Horizon, Rice County, Kansas, <i>Henry A. Ley</i> . . . . .                       | 197 |
| The Sheridan Test, Ellsworth County, Kansas, <i>Henry A. Ley</i> . . . . .                         | 199 |
| REVIEWS . . . . .  | 200 |
| THE ASSOCIATION ROUND TABLE . . . . .  | 201 |

### NUMBER 3

|  |     |
|--|-----|
| EARLY PENNSYLVANIAN DEPOSITS WEST OF THE NEMAH GRANITE RIDGE, KANSAS. Raymond C. Moore . . . . . | 205 |
| INTERIOR SALT DOMES OF LOUISIANA. W. C. Spooner . . . . .  | 217 |

|   | PAGE |
|---|------|
| THE ORIGIN OF THE FAULTS IN CREEK AND OSAGE COUNTIES, OKLAHOMA. |      |
| Lyndon L. Foley . . . . .                                       | 293  |
| SOME FEATURES OF RED-BED BLEACHING. Gail F. Moulton . . . .     | 304  |
| GEOLOGICAL NOTES  |      |
| The Wigglestick, <i>Donald C. Barton</i> . . . . .              | 312  |
| REVIEWS . . . . .   | 314  |
| THE ASSOCIATION ROUND TABLE . . . . .                           | 316  |
| MEMORIAL OF HENRY L. HAMILTON . . . . .                         | 358  |
| AT HOME AND ABROAD . . . . .                                    | 360  |

## NUMBER 4

|  |     |
|--|-----|
| THE SUBSURFACE GEOLOGY OF THE BIG LAKE OIL FIELD. E. H. Sellards<br>and Leroy T. Patton . . . . .                          | 365 |
| ORIGINAL SOURCE OF OIL IN COLOMBIA. F. M. Anderson . . . .   | 382 |
| OIL MINING. Edward Bloesch . . . . .   | 405 |
| REFLECTED BURIED HILLS IN THE OIL FIELDS OF PERSIA, EGYPT, AND<br>MEXICO. Sidney Powers . . . . .                          | 422 |
| OCCURRENCE OF BLACK OIL IN WYOMING. John G. Bartram . . .  | 443 |
| GEOLOGICAL NOTES   |     |
| Oil Fields of China: Acknowledgments and Correlations, <i>Frederick G.<br/>        Clapp and Myron L. Fuller</i> . . . . . | 449 |
| Annual Meeting of the Cordilleran Branch of the Geological Society<br>of America, <i>K. C. Heald</i> . . . . .             | 449 |
| New Zealand Oil Discovery, <i>Frederick G. Clapp</i> . . . . .   | 451 |
| REVIEWS . . . . .  | 452 |
| THE ASSOCIATION ROUND TABLE . . . . .  | 453 |
| AT HOME AND ABROAD . . . . .   | 454 |

## NUMBER 5

|   |     |
|---|-----|
| THE GEOLOGY AND OIL FIELDS OF ARCHER COUNTY, TEXAS. W. E.<br>Hubbard and W. C. Thompson . . . . .   | 457 |
| CORRELATIVE VALUE OF THE MICROLITHOLOGY AND MICROPALAEON-<br>TOLOGY OF THE OIL-BEARING FORMATIONS IN THE SUNSET-MIDWAY<br>AND KERN RIVER OIL FIELDS. Paul D. Goudkoff . . . . . | 482 |
| THE WHEELER RIDGE OIL FIELD. George M. Cunningham . . . .   | 495 |
| THE PLIOCENE AND PLEISTOCENE HISTORY OF THE BALDWIN HILLS,<br>LOS ANGELES COUNTY, CALIFORNIA. A. J. Tieje . . . . .   | 502 |
| CORE DRILLING FOR STRUCTURE IN THE NORTH MID-CONTINENT AREA.<br>H. G. Officer, Glenn C. Clark, and F. L. Aurin . . . . .  | 513 |

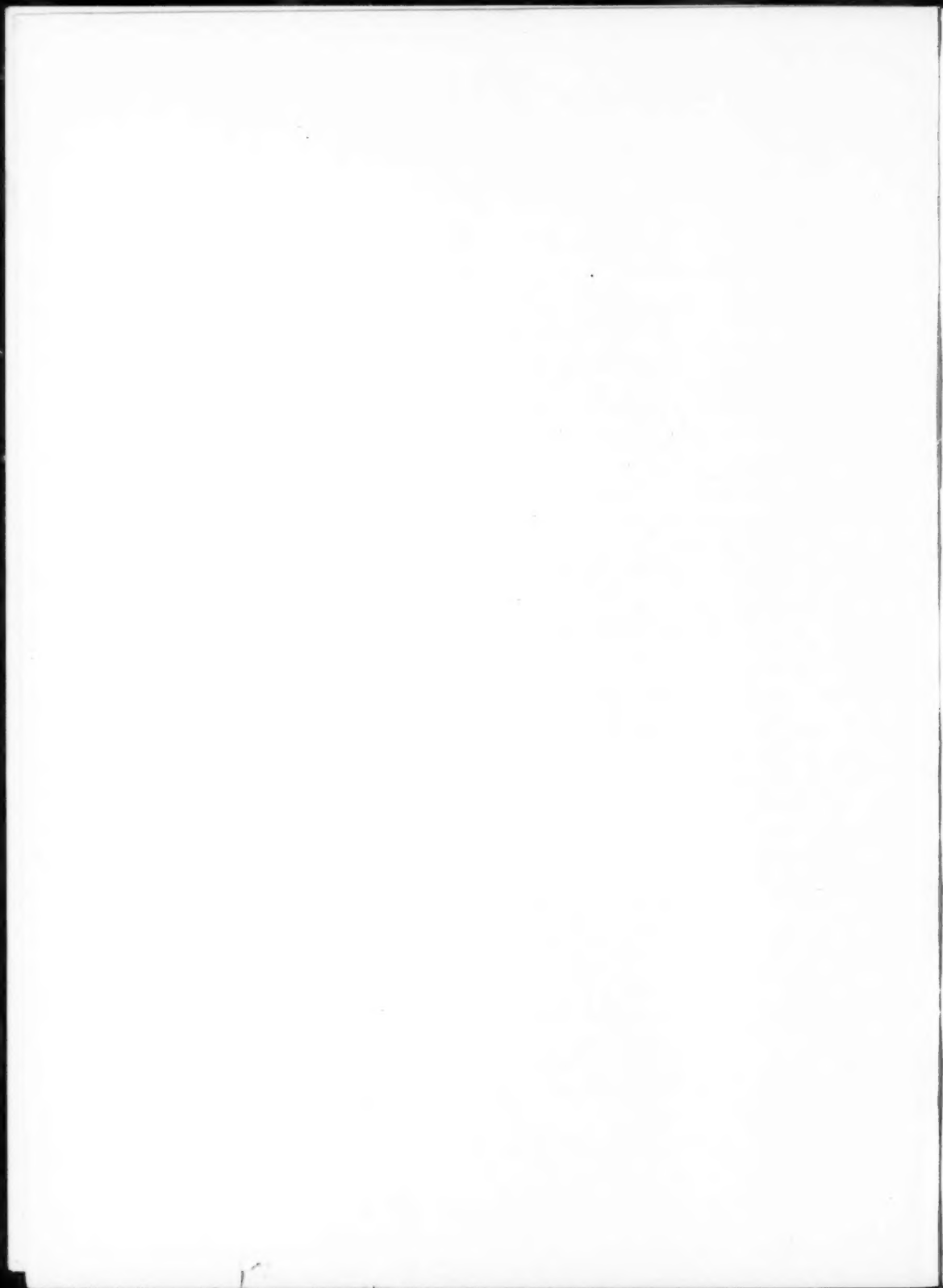
# CONTENTS OF VOLUME 10

vii

| GEOLOGICAL NOTES  |  | PAGE |
|---|--|------|
| Hauerite in a Salt-Dome Cap Rock, <i>Albert G. Wolf</i> |  | 531  |
| REVIEWS   |  | 533  |
| THE ASSOCIATION ROUND TABLE                             |  | 534  |
| AT HOME AND ABROAD                                      |  | 550  |

## NUMBER 6

|  |  |     |
|--|--|-----|
| NEW DATA ON THE COMANCHEAN STRATA OF CENTRAL KANSAS. <i>W. H. Twenhofel and A. C. Tester</i> |  | 553 |
| METHODS OF CORRELATION BY MEANS OF FORAMINIFERA. <i>J. J. Galloway.</i>                      |  | 562 |
| FURTHER OBSERVATIONS ON SHOESTRING OIL POOLS OF EASTERN KANSAS. <i>John L. Rich</i>          |  | 568 |
| THE FORAMINIFERA OF THE VELASCO SHALE OF THE TAMPICO EMBAYMENT. <i>Joseph A. Cushman</i>     |  | 581 |
| THE WOODBINE SAND OF TEXAS INTERPRETED AS A REGRESSIVE PHENOMENON. <i>Gayle Scott</i>        |  | 613 |
| LITHOLOGIC CHARACTER OF SHALE AS AN INDEX OF METAMORPHISM. <i>John H. Wilson</i>             |  | 625 |
| GEOLOGICAL NOTES   |  |     |
| Occurrence of Ordovician Sediments in Western Kansas, <i>Jon A. Udden</i>                    |  | 634 |
| DISCUSSION   |  |     |
| Early Pennsylvanian Sediments West of the Nehama Granite Ridge, Kansas, <i>A. R. Denison</i> |  | 636 |
| Some Features of Red-Bed Bleaching, <i>F. H. Lahce</i>                                       |  | 636 |
| REVIEWS  |  | 638 |
| ROUND TABLE  |  | 640 |
| AT HOME AND ABROAD   |  | 641 |



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## CONTENTS OF VOLUME 10

### PART 2

#### NUMBER 7

|   | PAGE |
|---|------|
| THOMAS OIL FIELD, KAY COUNTY, OKLAHOMA. Stuart K. Clark . . . . .   | 643  |
| DIAMOND DRILLS AND DIAMOND-DRILL EQUIPMENT FOR OIL STRUCTURE INVESTIGATION. Robert Davis Longyear . . . . .                               | 656  |
| THE GEOLOGIC HISTORY OF THE PANUO RIVER VALLEY AND ITS RELATION TO THE ORIGIN AND ACCUMULATION OF OIL IN MEXICO. Earl A. Trager . . . . . | 667  |
| THE RELATION OF FORAMINIFERA TO THE ORIGIN OF CALIFORNIA PETROLEUM. Thomas F. Stipp . . . . .   | 697  |
| DIAMOND DRILLING NEAR KERENS, NAVARRO COUNTY, TEXAS. F. W. DeWolf and Paul T. Seashore . . . . .  | 703  |
| WERE DIATOMS THE CHIEF SOURCE OF CALIFORNIA OIL? George M. Cunningham . . . . .   | 709  |
| AN EXPERIMENT WITH A DROP AUGER. Charles H. Row . . . . .   | 722  |
| DISCUSSION  |      |
| Origin of the Faults in Creek and Osage Counties, Oklahoma, E. L. Ickes . . . . .   | 727  |
| AT HOME AND ABROAD . . . . .  | 730  |

#### NUMBER 8

|   |     |
|---|-----|
| OIL AND GAS FIELDS OF THE TEXAS PANHANDLE. C. Max Bauer . . . . .                                   | 733 |
| PREDICTIONS OF THE FUTURE OF OIL POOLS BY EARLY WELLS. Willard W. Cutler, Jr. . . . .               | 747 |
| A CONTRIBUTION TO THE GEOLOGY OF LOS ANGELES BASIN, CALIFORNIA. J. E. Eaton . . . . .               | 753 |
| SUBSURFACE CRETACEOUS SECTION OF SOUTHWEST BEXAR COUNTY, TEXAS. Richard A. Jones . . . . .          | 768 |
| AN INTERESTING EXAMPLE OF A SURVEY OF A DEEP BORE HOLE. F. S. Hudson and N. L. Taliaferro . . . . . | 775 |
| THE SUBDIVISION OF THE ENID FORMATION. F. L. Aurin, H. G. Officer, and Charles N. Gould . . . . .   | 786 |
| OIL POSSIBILITIES OF THE BLACK HILLS REGION. E. G. Sinclair . . . . .                               | 800 |

| GEOLOGICAL NOTES  | PAGE |
|---|------|
| Fort Scott-Wetumka Correlation, <i>Edward Bloesch</i> . . . . .   | 810  |
| Combined Geologic and Oil-and-Gas Map of Wyoming . . . . .  | 812  |
| Notes on the Age and Correlation of the Moreno Shale, <i>J. A. Taff</i><br>and <i>G. D. Hanna</i> . . . . . | 812  |
| THE ASSOCIATION ROUND TABLE . . . . .   | 815  |
| AT HOME AND ABROAD . . . . .  | 817  |

---

### NUMBER 9

|  |     |
|--|-----|
| THE PERMIAN OF ARIZONA AND NEW MEXICO. <i>N. H. Darton</i> . . . . .   | 819 |
| OBSERVATIONS ON THE OCCURRENCE AND ORIGIN OF PETROLEUM IN<br>ARGENTINA AND BOLIVIA. <i>Robert Anderson</i> . . . . .   | 853 |
| MICROTHERMAL OBSERVATIONS OF SOME OIL SHALES AND OTHER CAR-<br>BONACEOUS ROCKS. <i>Taisia Stadnichenko</i> and <i>David White</i> . . . . .                    | 860 |
| THE GEOLOGIC STRUCTURE OF A PORTION OF THE GLASS MOUNTAINS OF<br>WEST TEXAS. <i>Philip B. King</i> . . . . .   | 877 |
| WILCOX SAND PRODUCTION, TONKAWA FIELD, OKLAHOMA. <i>Glenn C.</i><br><i>Clark</i> . . . . .   | 885 |
| OBSERVATIONS RELATING TO THE ORIGIN AND ACCUMULATION OF OIL<br>IN CALIFORNIA. <i>G. C. Gester</i> . . . . .  | 892 |
| A CRITICAL EXAMINATION OF THE EQUAL POUND LOSS METHOD AND OF<br>ESTIMATING GAS RESERVES. <i>Roswell H. Johnson</i> and <i>L. C.</i><br><i>Morgan</i> . . . . . | 901 |
| GEOLOGICAL NOTES   |     |
| Gas and Oil near Edna, Jackson County, Texas, <i>W. Armstrong Price</i>  | 905 |
| REVIEWS . . . . .  | 906 |
| THE ASSOCIATION ROUND TABLE . . . . .  | 909 |
| MEMORIAL OF WILLIAM KENNEDY . . . . .  | 913 |

---

### NUMBER 10

|  |     |
|--|-----|
| THE EFFECT OF PRESSURE ON THE MIGRATION AND ACCUMULATION OF<br>PETROLEUM. <i>F. M. Van Tuyl</i> and <i>R. C. Beckstrom</i> . . . . . | 917 |
| A QUICK METHOD FOR DETERMINING POROSITY. <i>W. L. Russell</i> . . . . .  | 931 |
| POROSITY AND CRUSHING STRENGTH AS INDICES OF REGIONAL ALTERA-<br>TION. <i>W. L. Russell</i> . . . . .                                | 939 |
| THE LYTTON SPRINGS OIL FIELD, CALDWELL COUNTY, TEXAS. <i>D. M.</i><br><i>Collingwood</i> and <i>R. E. Rettger</i> . . . . .          | 953 |
| CORAL REEFS IN THE OLIGOCENE OF TEXAS. <i>Alva Christine Ellisor</i> . . . . .   | 976 |

# CONTENTS OF VOLUME 10

vii

|  | PAGE |
|--|------|
| * NOTES ON THE QUADRANT FORMATION OF EAST-CENTRAL MONTANA.               |      |
| A. A. Hammer and A. M. Lloyd . . . . .                                   | 986  |
| GEOLOGICAL NOTES   |      |
| Discovery of Nigger Creek Oil Pool, Limestone County, Texas,             |      |
| <i>J. P. D. Hull</i> . . . . .   | 997  |
| A Soxhlet Extractor for Porosity Determinations, <i>Walter B. Lang</i> . | 998  |
| THE ASSOCIATION ROUND TABLE . . . . .                                    | 1001 |
| AT HOME AND ABROAD . . . . .   | 1005 |

## NUMBER 11

|   |      |
|---|------|
| A BRIEF OUTLINE OF SOME OIL-ACCUMULATION PROBLEMS. Alex W. McCoy . . . . .                                    | 1015 |
| THE EFFECT OF GRAVITATIONAL COMPACTION ON THE STRUCTURE OF SEDIMENTARY ROCKS. Hollis D. Hedberg . . . . .     | 1035 |
| OIL PROSPECTS IN NORTHEASTERN CHINA. Myron L. Fuller and Frederick G. Clapp . . . . .                         | 1073 |
| OIL PROSPECTS OF THE DESERT BASIN OF WESTERN AUSTRALIA. Frederick G. Clapp . . . . .                          | 1118 |
| OIL PROSPECTS OF THE NORTHWEST BASIN OF WESTERN AUSTRALIA. Frederick G. Clapp . . . . .                       | 1136 |
| PRELIMINARY REPORT ON THE GEOLOGY OF THE OIL FIELDS IN NORTH (RUSSIAN) SAKHALIN. Giichiro Kobayashi . . . . . | 1150 |
| THE RESULTS OF OIL PROSPECTING ON SAKHALIN ISLAND BY JAPAN IN 1919-25. L. P. Tolmachoff . . . . .             | 1163 |
| GEOLOGICAL NOTES  |      |
| Two New Salt Domes in Texas, <i>Wallace E. Pratt</i> . . . . .  | 1171 |
| Short Cuts in Picking Out and Sectioning Foraminifera, <i>Floyd and Helen Hodson</i> . . . . .                | 1173 |
| DISCUSSION  |      |
| Original Source of Oil in Colombia, <i>Otto Stutzer</i> . . . . .   | 1175 |
| Unusual Natural Gases, <i>Walter B. Lang</i> . . . . .  | 1176 |
| Oil Possibilities of the Black Hills Region, <i>W. W. Rubey</i> . . . . .                                     | 1177 |
| THE ASSOCIATION ROUND TABLE . . . . .   | 1178 |
| AT HOME AND ABROAD . . . . .  | 1184 |
| MEMORIALS OF JAMES V. HOWE AND BRYAN HENDON . . . . .   | 1188 |

## NUMBER 12

|   |      |
|---|------|
| CONSTRUCTION, THEORY, AND APPLICATION OF MAGNETIC FIELD BALANCES. C. A. Heiland . . . . . | 1189 |
| SCHWEYDAR-BAMBERG TYPES OF EÖTVÖS TORSION BALANCE. C. A. Heiland . . . . .                | 1201 |

|  | PAGE |
|--|------|
| TORSION-BALANCE PRINCIPLES AS APPLIED BY THE ORIGINAL EÖTVÖS                 |      |
| TORSION BALANCE. George Steiner . . . . .                                    | 1210 |
| OIL AND GAS PROSPECTS OF NEW ZEALAND. Frederick G. Clapp . . . . .           | 1227 |
| MECHANICS OF THE BALCONES AND MEXIA FAULTING. Lyndon L. Foley . . . . .      | 1261 |
| THE PROBLEM OF THE NATURAL REDUCTION OF SULPHATES. Edson S. Bastin . . . . . | 1270 |
| GEOLOGICAL NOTES   |      |
| Phoantagraph Model, <i>W. K. Cadman</i> . . . . .                            | 1300 |
| Unconformities in the Pennsylvanian, <i>Henry Hinds</i> . . . . .            | 1303 |
| Barometric Leveling, <i>Henry A. Ley</i> . . . . .                           | 1305 |
| Geophysics at Colorado School of Mines, <i>Max W. Ball</i> . . . . .         | 1305 |
| Oklahoma Survey, Seventh Field Conference, <i>Charles N. Gould</i> . . . . . | 1306 |
| REVIEWS . . . . .  | 1309 |
| THE ASSOCIATION ROUND TABLE . . . . .  | 1313 |
| AT HOME AND ABROAD . . . . .   | 1316 |
| MEMORIAL OF CHARLES STIRLING HUNTLEY . . . . .                               | 1322 |
| INDEX TO VOLUME 10 . . . . .   | 1323 |





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